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Design of a Software Sensor for Attitude and Angular Velocity Determination in a CubeSat Using only Solar Panels

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***Abstract*—In this paper a software sensor is designed in order to determine the attitude and the angular velocity of a CubeSat for active attitude control using only the solar panels. It consists of an algorithm to obtain the raw attitude measurement from solar panels' current and a state observer designed based on contraction theory. Relying on the synchronization as a means to attenuate the noise, this sensor may recover the "true" attitude and angular velocity states as the limit of the sensor performance.**

***Keywords*—** CubeSat, Solar panels, Contraction Theory, Synchronization, Attitude Determination, Software Sensor.

I. INTRODUCTION

Many space missions perfermed by large satellites currently may be accomplished by constellation of nano satellites in order to reduce the cost and increase the mission flexibility. This requires a precise active attitude controller. For active attitude control in CubeSats, besides the common requirements for a satellite, it necessitates a clean and reliable acquisition of the attitude and the angular velocity of the satellite with the additional constraints on weight, space and power consumption. To solve this problem many techniques have been developed. Some use deterministic methods as the case of TRIAD algorithm which was the first and simplest way to obtain the attitude using two or more measurements [1]. In [2] the Wahba problem was formulated and its solutions were proposed in order to determine the attitude of a satellite relied on the singular values decomposition [3]. The drawback of these methods is their low resolution and high sensibility to the measurement noise using typical attitude sensors for navigation. This motivates the need of filtering the measurements. New techniques have been developed, for instance, based on the observer theory like Extended Kalman Filter [4] or complement filter for nonlinear systems designed with Lyapunov method [5].

In a satellite, an attitude measurement can be acquired with typical sensors for navigation like IMU (inertial measurement unit) equipped with gyros, magnetometers and accelerometers. Other attitude sensors like sun sensors or star trackers are also frequently incorporated. The angular velocity of the satellite may be obtained with a gyroscope. However, in CubeSat applications, it is preferable to use lightweight sensors for the consideration of power consumption, space and weight.

This paper considers the problem of designing a software sensor for the attitude and the angular velocity determination in a CubeSat under the assumption that only the solar panels are used. It consists of solar panels for CubeSat power generation, a state estimator [6] and Julian Date calender [7] as shown in Fig. 1, where $V_s^B \in \mathbb{R}^3$ is the sun vector measured in the satellite's body frame, $V_s^I \in \mathbb{R}^3$ is the sun vector refereed to a inertial frame and $q_m \in \mathbb{R}^4$ is a measurement of the satellite's attitude represented in quaternions. First, the sun vector (V_s^B) is obtained from the current generated by the solar panels. This vector together with the solar vector refereed to the inertial frame given by Julian Date (V_s^I) using the algorithm described in [8] is employed to get a raw measurement of the CubeSats attitude in quaternion q_m using a real-time convex minimization algorithm [9]. Next, this raw attitude is fed into the state observer, designed based on contraction theory, to get a cleaner attitude and velocity estimate. The attenuation of the noise in attitude and velocity estimated increases as the number of solar panels increases and in theory, the noise might be completely removed from the estimate as the sensor performance limit. In practice, an acceptable level of attenuation of the measurement noise is achieved with a few solar panels as illustrated in the simulations.

Precise measurements of the vector V_s^I are available thanks to the Jet Propulsion Laboratory of NASA. However, it is desirable for reasons of communication bandwidth to use an algorithm on board to obtain an estimate of sun vector with a technique developed in the Astronomical Almanac [8]. This is because while the resource of bandwidth is going less accessible for the satellite related demand, the computation power of microprocessors is getting increasing and cheaper for this kind of applications.

II. PRELIMINARIES

A. Modeling of the Satellite

The dynamics of a satellite actuated by a set of three perpendicular reaction wheels represented as a rigid body in the space is described as

$$M\dot{\omega} = S(R^T h^I)\omega + \tau, \tag{1}$$

where $M \in \mathbb{R}^{3\times 3}$, $M = M^T$ is the inertia matrix, $\omega \in \mathbb{R}^3$ is the angular velocity vector, and $\tau \in \mathbb{R}^3$ the applied torque, all refereed to the satellite body frame {B}, and h^I angular moment refereed to the fixed inertial frame {I}. The matrix

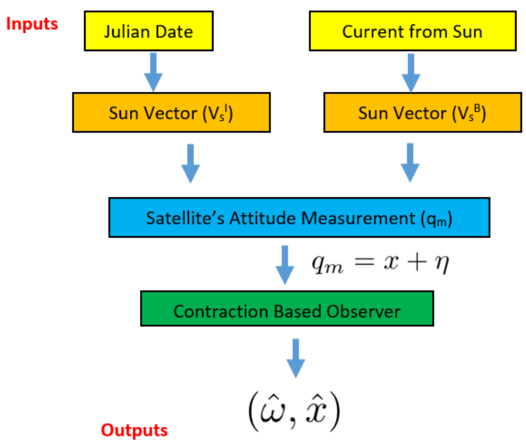

Fig. 1. Software Sensor, q_m is a measurement of the real quaternion x plus a zero-mean white noise n.

$S(a)$ defines a skew symmetric matrix for a given vector $a = [a_1 \; a_2 \; a_3]^T$ in the following way

$$S(a) = \begin{pmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{pmatrix}. \tag{2}$$

The inverse operation is defined as

$$a = S^{-1}(A) \tag{3}$$

for a skew symmetric matrix

$$A = \begin{pmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{pmatrix}. \tag{4}$$

The attitude of the satellite is represented by the rotation matrix $R \in SO(3) = \{R \in \mathbb{R}^{3\times3} | R^T R = I, det(R) = 1\}$ with respect to the inertial frame. In this paper, the rotation matrix is parametrized by quaternions, which is a minimum singularity-free representation of the rotation matrix [10].

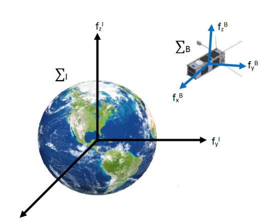

Fig. 2. Spacecraft body frame and inertial frame.

The kinematics model of the satellite under the parametrization of the attitude using quaternions is described as

$$\dot{x} = \frac{1}{2} J(x)\omega, \tag{5}$$

where x denotes a unit quaternion defined as

$$x = \begin{bmatrix} x_0 & x_1 & x_2 & x_3 \end{bmatrix}^T = \begin{bmatrix} x_0 & x_v^T \end{bmatrix}^T, \tag{6}$$

with $J(x)$ the analytic Jacobian

$$J(x) = \begin{bmatrix} -x_v^T \\ x_0 I_3 + S(x_v) \end{bmatrix}. \tag{7}$$

The rotation matrix R and the quaternion are related by the Rodrigues formula [11]

$$R = I_3 + 2x_o S(x_v) + 2S(x_v)S(x_v), \tag{8}$$

$$x_v = S^{-1}(R_s), \; R_s = \frac{1}{2\sqrt{1+tr(R)}}(R - R^T), \tag{9}$$

$$x_0 = \pm\sqrt{1 - x_v^T x_v}. \tag{10}$$

Since $x_0 = \pm 1$ corresponds to the same rotation matrix R, to avoid ambiguity the positive sign will be taken.

B. Contraction Theory Tools

The analysis of contraction is motivated by the fact that talking about stability does not require knowing what a nominal trajectory nor equilibrium is. Intuitively, a system is stable in a region in the state space if the initial conditions or temporary disturbances are somehow "forgotten", i.e., if the final behavior of the system is independent of the initial conditions. The following contraction and partial contraction theorems are used for the observer design.

Theorem 1. *(Contraction [12]). Consider the nonlinear system*

$$\dot{x} = f(x, t), \tag{11}$$

where $x \in \mathbb{R}^n$ is the state vector and f a smooth function. If the symmetric part of the Jacobian matrix of the system (11) *is uniformly negative definite, i.e., for some $\lambda > 0$,*

$$J_s = \frac{1}{2}\left(\frac{\partial f}{\partial x} + \frac{\partial f}{\partial x}^T\right) \leq -\lambda I, \quad \forall t \geq 0, \tag{12}$$

then, the system (11) *is contracting with convergence rate given by λ. Contraction implies that any two trajectories starting from different initial conditions converge exponentially to each other.*

Partial contraction, introduced in [13], is given next.

Theorem 2. *(Partial Contraction [13]). Consider a smooth non-linear system of the form*

$$\dot{x} = f(x, x, t), \tag{13}$$

and assume that the virtual system

$$\dot{y} = f(y, x, t), \tag{14}$$

is contracting with respect to y. If a particular solution of the virtual system verifies a smooth specific property, then all trajectories of the original x system verifies this property exponentially.

Partial contraction was a major step towards the application of the contraction analysis tools to solve control-related problems. For the observer design, it realizes a top-down approach: at the top-level, a contracting observer which may include non-measurable state variables, is first designed to ensure its desired (contraction) property. Next, the non-measurable states are substituted with known variables in the bottom-level in order to get an implementable version of the observers [14], [15].

III. Problem Formulation and Attitude/Velocity Determination

A. Problem Formulation

The problem addressed here is to design a software sensor using as input the current from solar panels and Julian Date calender to determine the attitude and angular velocity of a CubeSat taking into account the measurement noise. First, the raw attitude is determined using the real-time convex optimization with input data as the solar panels current and Julian Date calender. Next, a complete-order observer for both attitude and angular velocity is designed. Further, synchronization is employed as a means to attenuate the measurement noise [15] in the synchronized observer.

B. Attitude Determination

This subsection gives the development of an algorithm that determines the raw attitude from the the current measurement generated by the solar panels and Julian Date calender. The underline idea of the algorithm is as follows: the attitude of a satellite may be uniquely determined by the sun vectors obtained from both the body-frame (V_s^B), attached rigidly on the satellite and the initial-frame (V_s^I) with its center coincident to the center of the earth, from the relationship

$$\frac{V_s^I}{\parallel V_s^I \parallel} = R\frac{V_s^B}{\parallel V_s^I \parallel} + \frac{d}{\parallel V_s^I \parallel} \approx R\frac{V_s^B}{\parallel V_s^I \parallel}, \tag{15}$$

where d is the displacement from body frame to the inertial frame measured in the inertial frame. It is in the range of $200 - 2000$km for an LEO (Low Earth Orbit) satellite, which may be ignored compared to the Earth-Sun distance (about 150 million kilometers). The rotation matrix R will be obtained with the real-time convex minimization algorithm [9].

Considering a solar panel as an ideal sun sensor, i.e., neglecting the effects of temperature and tear of the panels, the measured current i is expressed as a function of incidence angle θ

$$i = i_{max} \cos\theta, \tag{16}$$

where i_{max} is the maximum current that can be generated by the panel when $\theta = 0$. So, measuring the current generated by a solar panel, it is possible to get the angle of incidence of the sun's rays.

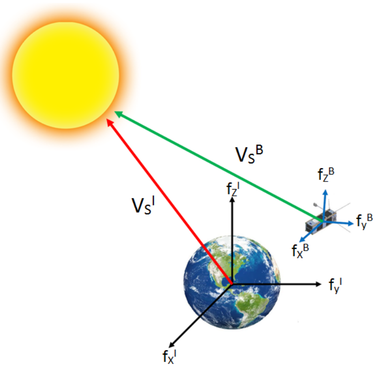

Fig. 3. Representation of the sun vector in body frame (V_s^B) and inertial frame (V_s^I)-

Now, in order to obtain the sun vector V_s^B, the standard algorithm described in [16] will be used. For this purpose, it is assumed that the CubeSat has at least six non-coplanar solar panels [1].

Define the normalized currents as

$$\frac{i}{i_{max}} = \cos\theta. \tag{17}$$

Then the estimated sun vector elements can be written as [16][2]

$$\bar{r}_{sun} = \begin{bmatrix} \frac{i_{m1}}{i_{max}} - \frac{i_{m4}}{i_{max}} \\ \frac{i_{m2}}{i_{max}} - \frac{i_{m5}}{i_{max}} \\ \frac{i_{m3}}{i_{max}} - \frac{i_{m6}}{i_{max}} \end{bmatrix}. \tag{18}$$

Finally, the vector V_s^B is determined by normalizing the vector $\bar{r}_{sun}$.

For the determination of the rotation matrix R it is necessary to get a sun vector of the earth measured from the inertial frame V_s^I as shown in equation (15). The current date in Julian Calender is employed for this purpose. From this the sun vector $\bar{r}_{\odot}$ in astronomical units [AU] is obtained, and so to get the vector V_s^I.

Next, the rotation matrix is estimated in real-time. The real-time convex optimization developed in [9] is used here, since this technique involves issues regarding to quadratic programming, well suited for real-time implementation. So, the problem of finding a estimated rotation matrix (R_y) of the real rotation matrix (R) turns to be minimizing the following function

$$R_y = arg\ min_{R\in SO(3)}(\| \frac{V_s^I}{\parallel V_s^I \parallel} - R\frac{V_s^B}{\parallel V_s^I \parallel} \|^2) \approx R_B^I, \tag{19}$$

subject to the following restriction

$$\parallel R_y \parallel = 1. \tag{20}$$

In the software sensor, the Convex optimization algorithm in real-time is implemented using the CVX (Convex Optimization Toolbox) running in Matlab similar to that shown in [9]. Thus R_y, an estimated R, is obtained. Finally, the transformation from $SO(3)$ to quaternion is performed, obtaining the raw attitude q_m, which is the input to the state observer designed in the next section.

IV. Observer Design

In this section two observers are described: complete-order and synchronized observer [6]. Due to the space limitation, the reader is referred to that paper for their proofs.

A. Complete-order observers

Consider the attitude dynamics (1) and (5). The complete-observer is given by

$$\begin{aligned} \dot{\hat{w}} &= \left[S(\mathbf{R}^T h^I) - K_{11} J_f^T J\right] \hat{w} - K_{11}\Gamma(J - J_f)^T x \\ &\quad + K_{12}(x - \hat{x}) + \tau, \\ \dot{\hat{x}} &= (I_3 - K_{21})\, J(x)\hat{w} + K_{22}(x - \hat{x}), \end{aligned}$$

[1]This is always technically possible by a proper design of the solar power system.

[2]If more that 6 solar panels are available, the redundant currents will be used for the synchronized observed described in Subsection IV-B.

where $\hat{w} = M^{-1}(\bar{w} + K_{11} J_f^T x)$and $\hat{x} = \bar{x} + K_{21} x$ and the gain matrices K_{11}, K_{12}, K_{21} and K_{22} are

$$K_{11} = K_{11}^T > 0, \quad (21)$$
$$K_{22} = K_{22}^T > 0, \quad (22)$$
$$K_{12} = [(I_4 - K_{21})J(x)]^T = J^T(x)(I_4 - K_{21}), \quad (23)$$
$$K_{21} = K_{21}^T = k_{21} I_4, \; k_{21} < 1. \quad (24)$$

Thus J_f is defined as

$$\dot{J}_f = (J - J_f)\Gamma, \;\; J_f(0) = J(x(0)), \quad (25)$$

and $\Gamma = \Gamma^T > 0$ the filter gain matrix. For simplicity it is defined $\Gamma = \gamma I_3$, with $\gamma > 0$ a constant.

The output of the observer is given by

$$\hat{w} = M^{-1}(\bar{w} + K_{11} J_f^T \hat{x}), \quad (26)$$
$$\hat{x} = \frac{1}{(1 - k_{21})}\bar{x}. \quad (27)$$

Theorem 3. *The complete-order observer given above is contracting, i.e., for any initial conditions $\hat{w}(0)$ and $\hat{x}(0)$, its trajectory converges exponentially to the trajectory of the real system provided that $\lambda_1 \triangleq \lambda_{min}(K_{11}) - \epsilon_J \lambda_{max}(K_{11}) > 0$ for some $0 < \epsilon_J << 1$.*

B. Synchronized Observer

In order to prevent the power system from shutting down, several solar panels are mounted in one face of the satellite. This method is currently used to increase the amount of stored solar energy [17]. Taking this advantage, a synchronized observer, designed by synchronizing a group of complete-order observers (see, for more details Appendix of [15]) may attenuate further the effect from the current measurement noise from the solar panels.

Each observer is fed by an independent measurement of the attitude acquired by the i-the solar panel $x_i = x + n_i$, with n_i white independent Gaussian noise with zero mean. For $i = 1, 2, ..., N$ and $J = J(x_i)$ the synchronized observer is given by

$$\dot{\bar{w}}_i = \left[S(\mathbf{R}^T h^I) - K_{11} J_f^T J\right]\hat{w}_i - K_{11}\Gamma(J - J_f)^T x_i + K_{12}(x_i - \hat{x}_i) - K_s \sum_{j=1}^{N}(\hat{w}_i - \hat{w}_j) + \tau, \quad (28)$$
$$\dot{\bar{x}}_i = (I_3 - K_{21})\, J(x)\hat{w}_i + K_{22}(x_i - \hat{x}_i) - K_s \sum_{j=1}^{N}(\hat{x}_i - \hat{x}_j). \quad (29)$$

with $\hat{w}_i = M^{-1}(\bar{w}_i + K_{11} J_f^T x_i)$ and $\hat{x}_i = \bar{x}_i + K_{21} x_i$. The output of the observer is given by

$$\hat{w}_i = M^{-1}(\bar{w}_i + K_{11} J_f^T \hat{x}_i), \quad (30)$$
$$\hat{x}_i = \frac{1}{(1 - k_{21})}\bar{x}_i. \quad (31)$$

where N is the observers number and $K_s = K_s^T > 0$ is the coupling gain.

Theorem 4. *Consider the synchronized observer (28)-(31). Let the state estimate be*

$$\hat{X} = [\hat{\mathbf{w}}^T \; \hat{\mathbf{x}}^T]^T = \frac{1}{N}\sum_{i=1}^{N}\hat{\mathbf{X}}_i, \quad (32)$$

with $\hat{\mathbf{X}}_i = \left[\hat{\mathbf{w}}_i^T \; \hat{\mathbf{x}}_i^T\right]^T$. Then under the same condition as in Theorem 3, $(\hat{\mathbf{X}} - \mathbf{X}) \to \mathbf{N}_0(1/N)$ exponentially, where $\mathbf{N}_0(1/N)$ is a neighborhood of the origin with ratio inversely proportional to $1/N$ and X is defined similarly as $\hat{X}$.

This result establishes a theoretical limit for the observer performance as the number of synchronized observers N goes to infinite. In practice, as illustrated in the simulation, a few complete-order observers need to be synchronized to achieve an acceptable level of noise attenuation. Although being easily done for large satellites by mounting more solar panels in each face, this brings certainly technology challenges for nano-satellites power system designs.

V. Simulation

To show the performance of the proposed software sensor, several simulations were carried out in an LEO CubeSat actuated with three perpendicular reaction wheels. First to test the performance of the complete-order and the synchronized observer, a noisy quaternion measurement is fed to both the complete-order and the synchronized observer. Next, to test the software sensor as a whole system, in the simulation the algorithm to get the sun vector in the inertial frame V_s^I, the algorithm to get the sun vector in the body frame V_s^B from the solar panels and the real time convex optimization algorithm to get a measurement of the attitude in quaternions were implemented together with the complete-order observer.

The parameters of the satellite for all simulations were: satellite mass, $m = 1.33[kg]$, dimensions $10cm \times 10cm \times 10cm$. A constant angular momentum is considered in the inertial reference system $h^I = [\frac{1}{\sqrt{2}} \;\; \frac{1}{\sqrt{2}} \;\; 0]^T \; [kg\; m^2/s]$. Given the dimension of the satellite and its geometry , the inertia matrix was taken as

$$M = \begin{bmatrix} 0.0022 & 0 & 0 \\ 0 & 0.0022 & 0 \\ 0 & 0 & 0.0022 \end{bmatrix} [Kg - m^2]. \quad (33)$$

The initial conditions for the satellite were $\omega(0) = [0.1 \;\; 0.15 \;\; -0.15]^T \; [\frac{rad}{seg}]$ and $x(0) = [0.5 \;\; 0.5 \;\; 0 \;\; \sqrt{0.5}]^T$; and for the observers $\hat{\omega}(0) = [0 \;\; 0 \;\; 0]^T \; [\frac{rad}{seg}]$ and $\hat{x}(0) = [1 \;\; 0 \;\; 0 \;\; 0]^T$. The value of the filter gain was $\Gamma = 5I_4$ and gain matrices were $K_{11} = 0.1I_3$, $K_{22} = 100I_3$, $K_{21} = 0.1$.

In Fig. 4, it is shown the measurement of the raw attitude in quaternion q_m, given by the sum of the real attitude x plus a zero-maen Gaussian white noise with power density 0.01. Fig. 5 shows the estimated angular velocity obtained by the complete-order observer (in color) and the real angular velocity (in black). Fig. 6 shows the estimated attitude. Observe that the estimates converge in about two seconds to the real ones, however, the effect of measurement noise is noticeable.

Next, a simulation with the synchronized observer was performed. The value of the filter gain and gain matrices were the same as in the previous simulations. The synchronization gain was $K_S = 100$. Fig. 7 and Fig. 8 show the estimated angular velocity and attitude of $N = 10$ synchronized complete-order observers. Notice that compared to the complete-order observer a remarkable improvement in the performance of the observer is obtained.

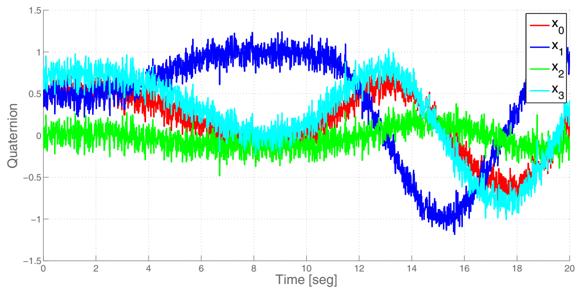

Fig. 4. The raw quaternion obtained by solar panel currents and Julian Date

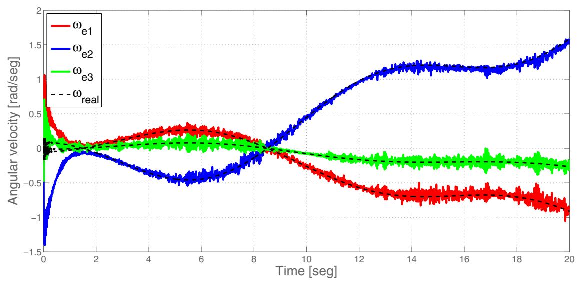

Fig. 5. Estimated Angular Velocity - Complete-order Observer

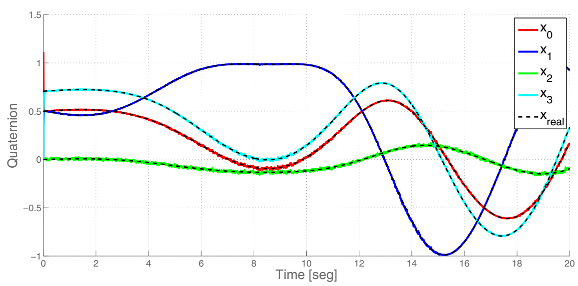

Fig. 6. Estimated Quaternion - Complete-order Observer

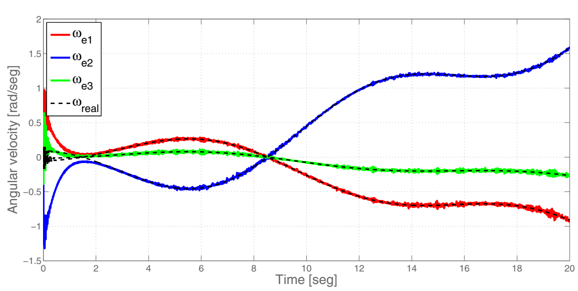

Fig. 7. Estimated Angular Velocity - Synchronized Observer

Finally, the performance of the software sensor as a whole system is tested using the same set of parameters as in the previous simulations. In this case the inputs were the solar panels currents and the Julian Date, from which the sun vector in the inertial frame and the body frame were calculated first. Then relying on the real-time convex optimization algorithm in [9] a raw quaternion measurement was obtained, which was fed to the observers. The output of this software sensor are the estimated angular velocity and attitude. Fig. 9 and 10 shown the performance of the software sensor, where the complete-order observer was employed.

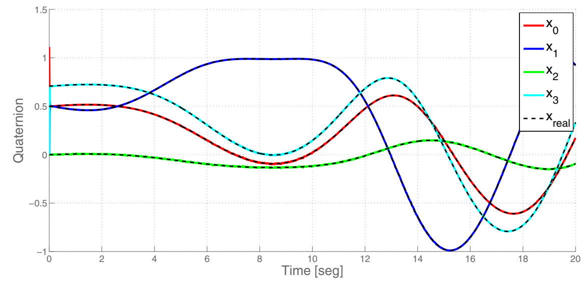

Fig. 8. Estimated Quaternion - Synchronized Observer

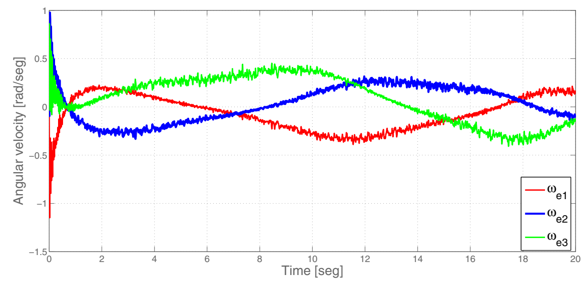

Fig. 9. Estimated Angular Velocity - Complete System

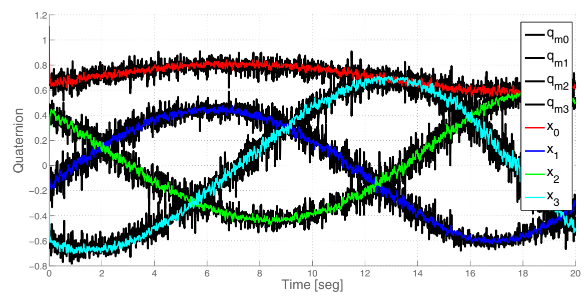

Fig. 10. Estimated Quaternion - Complete System

VI. Conclusion

This paper contributes with a software sensor design to determine the attitude and the angular velocity for attitude control in a CubeSat. The input to this sensor are the solar panels' currents. The output are the angular velocity estimate and the attitude estimate. These estimates converge exponentially to their true values in the noise-free case. When the measurements are noisy, this result may be achieved as the number of synchronized observers goes larger.

The main drawback of this software sensor is the need of a precise satellite model. Estimating both the models parameters and the state is under research and will be reported in a future work.

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