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Hybrid satellite position estimator using self-induced dither for SATCOM On The Move

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Abstract: The only way to insure a good satellite communication data rate on a moving vehicle is to maintain an antenna bore-sight in the satellite direction. To do so, the antenna is mounted on an Antenna Positioning Systems (APS). The APS is a motorized gimbal that make the antenna move in order to maintain a proper pointing, regardless the vehicle movements. This kind of satellite communication is called SATCOM On The Move (SOTM).

In this paper, an hybrid pointing strategy, using least squares identification and gyroscopes is proposed and tested through realistic simulation. The main difference with other strategies is that the scanning is made using only the motion due to measurement noise and gyroscope drift, making unnecessary the introduction of a pointing dither on purpose, as it is usually done. Such a dither is referred as self-induced dither.

The main advantage of this strategy is its robustness with respect to non-linearities due to mechanical defects since no precise dither trajectory has to be followed. Another benefit is that attitude measurements are not used during tracking, making the strategy proposed especially interesting for low cost applications.

Keywords: Tracking Systems, SATCOM On The Move, Least Squares Estimator, Inertially Stabilized Platform, Antennas, Identification.

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1. INTRODUCTION

In order to insure an acceptable satellite communication on a moving vehicle (planes, drones, land vehicles, vessels ...), antennas must be steered toward a satellite. To do so, antennas are mounted on stabilized platforms called Antenna Positioning Systems (APS). The requirements in term of pointing accuracy depend on the wave frequency and on the antenna size. For the application studied in the following paper, the frequency band and the antenna size leads to a required pointing accuracy of approximately 0.3 degrees (Debruin (2008)). The mis-pointing should not overcome 0.8 degrees, in order not to lose the communication link. The accuracy must be insured while the vehicle is moving. Therefore, the antenna must track the satellite in real time: it is the tracking phase.

Many pointing strategies exist, for fixed and mobile stations (Hawkins et al. (1988)). An *Open loop* pointing strategy is based only on a vehicle attitude measurement (Nazari et al. (2005)). A *Closed loop* pointing strategy is based on the *Signal over Noise Ratio* (SNR) measurement, which represents the strength of the satellite communication signal. The point of tracking is to maximize the SNR. These techniques are Monopulse, Conical Scan (Gawronski and Craparo (2002)) and Step Tracking (Laine (2000)). Pointing strategies that use both attitude and

SNR measurement are called *hybrid strategies* (Timothy et al. (2002), Deike (2010)).

An Open loop pointing requires a high quality Inertial Navigation System (INS) to provide an attitude measurement, without heavy constraints on the APS mechanical design. On the contrary, a closed loop strategy such as Conical Scan does not requires an attitude measurement but it needs to introduce a circular pointing movement in order to vary the SNR. This voluntary movement is called a dither and is needed in order to insure the identifiability of the satellite position. Therefore, the APS defects (backlash, mechanical compliance, imbalance and friction) have to be minimized in order to be able to follow a dither trajectory precisely.

The pointing strategy proposed in this paper aims to reduce the cost of an APS using an hybrid pointing strategy that is robust to mechanical defects, without the use of attitude measurement, while respecting the same requirements in term of pointing accuracy. This is achieved using self-induced dither, introduced only by measurement error and noise.

First, a brief description of the APS is made. Then the proposed algorithm is described: the satellite position estimator uses a 2D curve least squares fitting and gyroscope measurements to estimate the satellite direction. Finally, the simulation model is described and the simulation results are shown in order to illustrate the benefit of the approach.

2. ANTENNA POSITIONING SYSTEM (APS)

In this section, a description of the architecture of the APS is made and the sensors available are described. A block diagram is shown on figure 2.

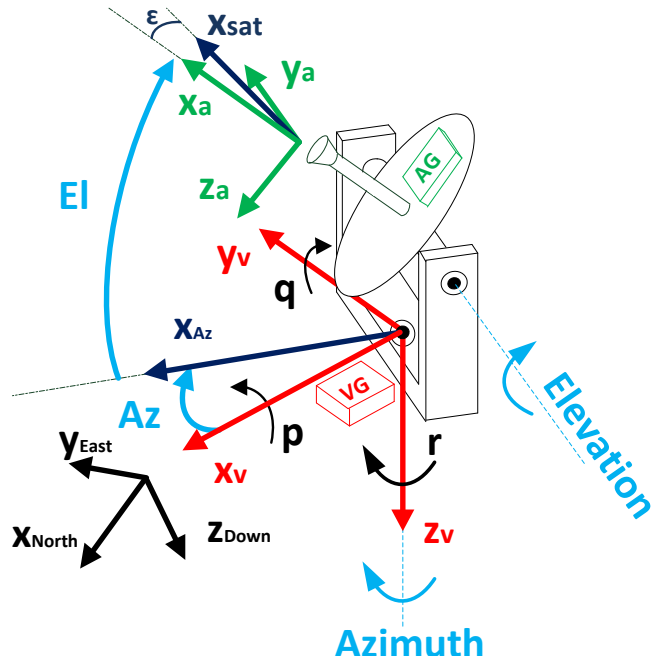


Fig. 1. Notations and frames of an APS

is called Azimuth. Az is defined as the angle between x_v and x_{Az} . The second one is horizontal and is called Elevation. El is defined as the angle between x_{Az} and x_a (see figure 1).

- **Antenna Pattern:** This block represents the loss of SNR caused by mis-pointing. It depends on the antenna size and the wave frequency.
- **Proposed satellite position estimator:** The strategy presented in the manuscript is based on a least squares method, using SNR and measured axis angles (Az, El) in order to estimate the position of the satellite (see section 3). It updates the least squares measurement vector at every sample time t_0 using the measured vehicle angular rates (p, q, r) (see section 4). The output of the proposed algorithm is then $(\widehat{Az}^*, \widehat{El}^*)$, an estimation of the positions (Az^*, El^*) that maximizes the SNR.

$R_{NED} = (x_{North}, y_{East}, z_{Down})$, on figure 1, is a fixed frame with respect to the ground, with its x axis pointing North, its y axis pointing East and its z axis pointing Down.

The pointing error ε , also called mis-pointing, is defined as the angle between the pointed direction x_a and the true satellite direction x_{sat} . See figure 1. ε is expressed as:

$$\varepsilon = \sqrt{\cos^2(El) \cdot (Az^* - Az)^2 + (El^* - El)^2} \quad (1)$$

The following sensors are available:

- **The vehicle gyroscopes (VG on figure 1)**, measuring the vehicle angular rates (p, q, r), with respect to R_{NED} , expressed in the vehicle body frame $R_v = (x_v, y_v, z_v)$.
- **The antenna gyroscopes (AG on figure 1)**, measuring the angular rates of the antenna with respect to R_{NED} in the antenna body frame called $R_a = (x_a, y_a, z_a)$. x_a is the pointed direction.
- **Two encoders on the motors**, that measure the angles of the mechanical axes (Az, El).
- **The SNR receiver** that measures the SNR, in dB. It enables the system to measure the communication quality. In practice, this measurement is very noisy and has to be filtered.

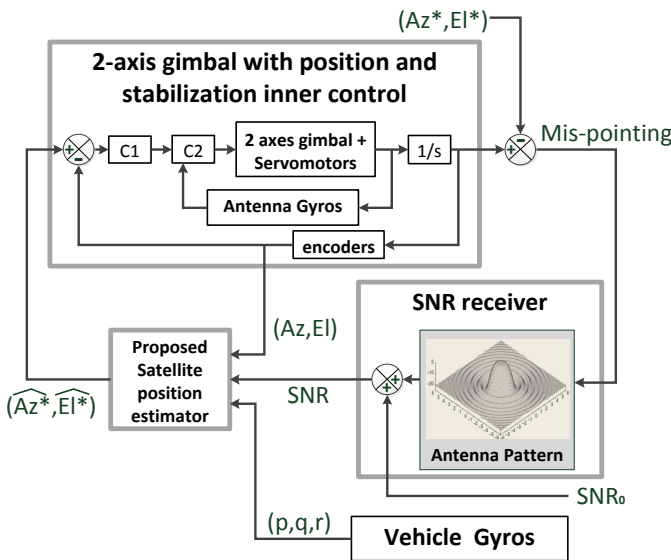


Fig. 2. Block diagram of an APS with the proposed algorithm

- **2-axis gimbal with position and stabilization inner control:** These blocks represent the two controlled mechanical axes that are steered in order to point the antenna toward the satellite. The block $C1$ is the position controller, that uses encoders position measurements. The block $C2$ is the stabilization controller, that uses antenna gyroscopes (AG on figure 1) for short term stabilization. $C1$ and $C2$ are both proportional integrals controllers. As shown on figure 1, the first APS axis is vertical and

3. CURVE FITTING USING LEAST SQUARES METHOD

The point of 2D curve fitting is to scan the sky in order to find the positions (Az^*, El^*) that maximizes the SNR. The SNR is measured at every sample time t_0 and linked with two angle positions (Az, El) . Over a sufficient observation window T and thanks to a least squares estimator, the antenna pattern can be identified in space and leads to an estimation of the positions $(\widehat{Az}^*, \widehat{El}^*)$.

The antenna pattern is defined as follow:

$$SNR = -p.\cos^2(El).(Az^* - Az)^2 - p.(El^* - El)^2 + SNR_0 \quad (2)$$

The parameter p is known, constant and depends on the shape of the antenna. SNR_0 is the unknown maximum SNR available. $SNR = SNR_0$ when $(Az, El) = (Az^*, El^*)$.

Developing (2), and averaging El over the observation window T ($\cos^2(El(t)) \approx \cos^2(El_0)$), the linearized antenna pattern can be expressed as follow:

$$SNR + p.\cos^2(El_0).Az^2 + p.El^2 = 2.p.\cos^2(El_0).Az^*.Az + 2.p.El^*.El - p.\cos^2(El_0).Az^{*2} - p.El^{*2} + SNR_0 \quad (3)$$

If the maximum to be found SNR_0 and the positions (Az^*, El^*) are constant over an observation window T , the problem can be expressed as follow:

$$y = (Az \ El \ 1) \cdot \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix} = DX \quad (4)$$

with :

$$\begin{aligned} \eta_1 &= 2.p.\cos^2(El_0).Az^* \\ \eta_2 &= 2.p.El^* \\ \eta_3 &= -p.\cos^2(El_0).Az^{*2} - p.El^{*2} + SNR_0 \\ y &= SNR + p.\cos^2(El_0).Az^2 + p.El^2 \end{aligned}$$

$$D = (Az \ El \ 1) \text{ and } X = \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix}$$

Using the estimation of X , the satellite position is found :

$$Az^* = \frac{\eta_1}{2.p.\cos^2(El_0)} \quad El^* = \frac{\eta_2}{2.p} \quad (5)$$

The measurement is repeated n times, over the observation window T with the sample time t_0 ($n = \frac{T}{t_0}$). The problem is then expressed as follow:

$$Y = WX + e \quad (6)$$

Y is a $n \times 1$ vector containing n measurements of y . W is a $n \times 3$ matrix called observation matrix, containing n lines of the matrix regressors D . e is a $n \times 1$ error vector caused by the noise measurement and the modeling error.

Equation (6) is an over determined linear system, obtained by measurements at different times.

The solution \hat{X} is searched in order to minimize the Euclidian norm of the vector e of (6):

$$\hat{X} = \underset{X}{\operatorname{argmin}}(\|e\|) = \underset{X}{\operatorname{argmin}}(\|Y - WX\|)$$

The solution of (7) is given by:

$$\hat{X} = (W^T W)^{-1} W^T Y \quad (7)$$

The identifiability of X depends on the observation matrix rank. The rank of W is defined as the number of independent matrix columns. The rank deficiency of W can come from two origins:

- A structural rank deficiency which stands for any samples of W . This is the structural parameter identifiability problem which is solved using the minimal parameters.
- Data rank deficiency due to a bad choice of the exciting trajectory which is sampled in W . This is the problem of optimal measurement strategies.

Back to the physical system studied here, the existence and the uniqueness of the solution of (7) requires that the antenna bore-sight moves away from the satellite direction in order to allow a sufficient number of different measurements to insure the identifiability of the solution \hat{X} . Considering that this pointing dither allows a better identifiability of (Az^*, El^*) and that it also degrades the pointing accuracy, a trade-off has to be found.

In the proposed algorithm, the dither comes from measurement noise (SNR and antenna gyroscopes). This dither does not have to be followed precisely. In that way, the dither is self-induced by the system. The antenna gyroscopes noise makes the stabilization inner control noisy, which create a part of the self-induced dither. In addition, because of the noise in the SNR measurement, the estimation (\hat{Az}^*, \hat{El}^*) is also noisy, which induces the other part of the self-induced dither. The sensors output filters are designed in order to insure an acceptable trade-off between pointing accuracy and (Az^*, El^*) identifiability.

So far, the hypothesis of constant positions (Az^*, El^*) over the observation window has been made. Because of the application in SATCOM On the Move, the positions (Az^*, El^*) are likely to change. To tackle this issue, the choice of an hybrid pointing strategy using gyroscopes has been made.

4. VEHICLE ANGULAR RATE PROPAGATION IN THE LEAST SQUARES FIT

Thanks to the three vehicle gyroscopes (VG on figure 1), the movement of the vehicle, and therefore, the variation of the maximum is measured. The least squares matrices Y and W of (6) can then be updated every sample time t_0 in order to "move the curve fitting" as the vehicle moves. The angular rate propagation is described in this section.

(p_a, q_a, r_a) , the angular rates (p, q, r) expressed in the R_a frame are calculated using the following expression:

$$\begin{pmatrix} p_a \\ q_a \\ r_a \end{pmatrix} = R_{z_v}(Az^*) R_{y_a}(El^*) \begin{pmatrix} p \\ q \\ r \end{pmatrix} \quad (8)$$

with $R_{z_v}(Az^*)$, $R_{y_a}(El^*)$ the rotation matrix about z_v and y_a axis of the angles Az^* and El^* , figure 1.

Because the tracking presented in this document is for geosynchronous satellite, the angular rate of the antenna with respect to R_{NED} on the y_a and z_a axis, respectively named \dot{y}_a and \dot{z}_a , should be zero for a perfect pointing. The angular rate (Az^*, El^*) that rejects perfectly the vehicle movement can then be calculated as:

$$\begin{pmatrix} p_a \\ q_a \\ r_a \end{pmatrix} + R_{y_a}(El^*) \begin{pmatrix} 0 \\ 0 \\ \dot{Az}^* \end{pmatrix} + \begin{pmatrix} 0 \\ \dot{El}^* \\ 0 \end{pmatrix} = \begin{pmatrix} \dot{x}_a \\ \dot{y}_a \\ \dot{z}_a \end{pmatrix} = \begin{pmatrix} \dot{x}_a \\ 0 \\ 0 \end{pmatrix} \quad (9)$$

With \dot{x}_a , the uncontrolled angular rate with respect to x_a , that have no impact on the pointing. (\dot{Az}^*, \dot{El}^*) can then be written :

$$\dot{Az}^* = -\frac{r_a}{\cos(El^*)} \quad \dot{El}^* = -q_a \quad (10)$$

Obviously, to calculate (\dot{Az}^*, \dot{El}^*) , Az^* and El^* have to be known. The estimator output $(\widehat{Az}^*, \widehat{El}^*)$ is used in order to calculate $(\widehat{\dot{Az}^*}, \widehat{\dot{El}^*})$ in equation (10).

These angular rates are integrated into the W and Y matrices of (6), every sample time t_0 .

$$\begin{pmatrix} Az_1 \\ \vdots \\ Az_n \end{pmatrix}_{t+t_0} = \begin{pmatrix} Az_1 \\ \vdots \\ Az_n \end{pmatrix}_t + \widehat{\dot{Az}^*} t_0 \quad (11)$$

$$\begin{pmatrix} El_1 \\ \vdots \\ El_n \end{pmatrix}_{t+t_0} = \begin{pmatrix} El_1 \\ \vdots \\ El_n \end{pmatrix}_t + \widehat{\dot{El}^*} t_0 \quad (12)$$

A trade-off has to be found between observation window T and the vehicle gyroscopes' drift. A longer observation window T leads to a better identification of (Az^*, El^*) thanks to a greater amount of measurements. The vehicle gyroscopes' drift introduces a position error that increases over time in the measurements. The observation window T must be large enough in order to allow a good estimation of (Az^*, El^*) but the vehicle gyroscopes' drift error must be small enough to remain acceptable over the time T .

In any case, an algorithm such as a Kalman filter has to be used in order to remove the low frequency drift of the VG (Sutherland Jr and Gelb (1968)).

5. SIMULATION

The simulation model used in this study is widely based on a model created, validated and currently used by Thales Communication and Security (TCS). The mechanical model includes several assumptions in order to make the simulation more realistic.

5.1 APS mechanical model

The dynamics of the two-axis APS are modeled using the Simulink toolbox SimMechanics.

Friction (dry and viscous) of the motors and the driven axes are taken into account. The total amount of azimuth dry friction seen by the motor represents 25% of the nominal torque. This dry friction torque is then divided into two parts: 10% of the dry friction is on the motor shaft and 90% is on the driven axis. The elevation dry friction torque represents 15% of the motor nominal torque. The same friction division is applied on the elevation axis as on azimuth axis.

The gear backlash values have been validated on an actual APS.

The mechanical compliance used is the motor shaft torsion flexibility.

The axis imbalances are modeled using SimMechanics tools.

5.2 Gyroscope models

An Allan variance and Power Spectral Density (PSD) analysis was used to identify and recreate in simulation the sources of errors of an actual gyroscope sensor (IEEE-standard (1998)).

The antenna gyroscope (AG) models are made in order to fit the raw measurements of the actual sensors. The noise and drift of this gyro will be used as dither for the proposed algorithm

The vehicle gyroscope (VG) models are made in order to fit the output of the embedded Kalman Filter of the actual sensors (section 4). To do so, the Kalman Filter uses magnetometers and accelerometers.

5.3 Encoder model

The encoders' measurement is discrete and is carried out on the motors shaft. This leads to a position measurement error on (Az, El) due to backlash and shaft torsion.

5.4 Vehicle movements

The vehicle movements are the movements that the tracking has to compensate in real time. The movements used in the simulation are the attitudes (Euler angles) on figure 3. These movements come from an aircraft flight simulation.

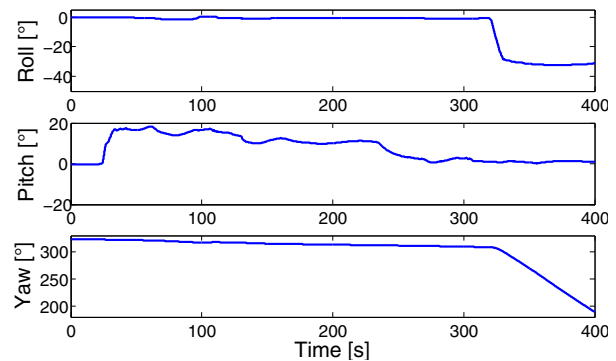


Fig. 3. Attitude of a simulated aircraft flight

5.5 Simulation results

The simulation is carried out with the model and the movements presented section 5. To insure a good enough communication data rate, the root mean square (RMS) pointing error must remain under 0.3 degrees. The maximum mis-pointing is also crucial because over a certain value, the communication link is lost. In the application studied here the maximum acceptable mis-pointing is 0.8 degrees.

In order to study the sources of pointing errors, three simulations are studied:

- **Simulation (a)** is carried out using the new hybrid satellite position estimator, with mechanical/sensor defects, in order to study the overall pointing accuracy of the strategy presented in this document.

- **Simulation (b)** is carried out with mechanical/sensor defects, but without using the proposed satellite position estimator. The positions (Az^* , El^*) are supposed to be known. The point of this simulation is to find out the error due to mechanical defects. This simulation gives an estimate of the accuracy of the inner position and stabilization control, presented figure 2.
- **Simulation (c)** is carried out without mechanical/sensor defects, using the proposed satellite position estimator. The point of this simulation is to find out the pointing error caused only by the estimation error. The noise of the SNR measurement and the antenna gyroscopes remain, in order to create the needed dither. This simulation aims to estimate the accuracy of the estimator algorithm presented in this document.

The figure 4 represents the mis-pointing over time for the three simulations presented above.

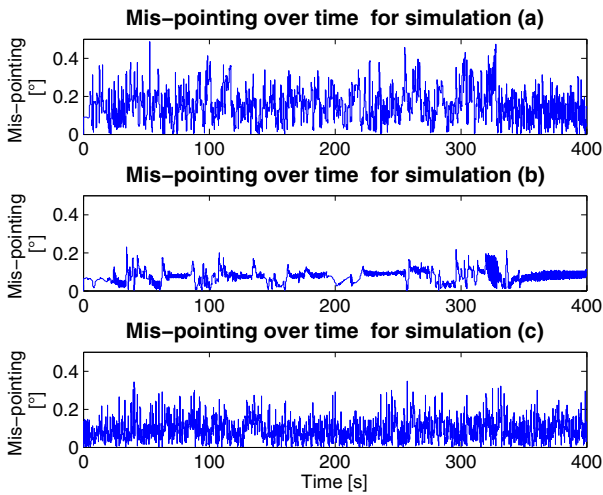


Fig. 4. Mis-pointing over time for the simulated flight scenario

The results of the three simulations are presented in table 1.

	Mis-pointing RMS	Mis-pointing Max
Simulation (a)	0.17	0.48
Simulation (b)	0.08	0.23
Simulation (c)	0.10	0.37

Table 1: Pointing accuracy in degrees for the three simulations

First, simulation (a) is studied since it represents the overall accuracy of the pointing on a realistic simulated system: figure 4 and table 1 show that the antenna remains correctly pointed toward the satellite, with a RMS mis-pointing of 0.17 degrees. This means that the accuracy of the pointing strategy presented in this document allows an acceptable communication data rate. The maximum mis-pointing seen during this simulation is 0.48 degrees, which is small enough to maintain the communication link during the simulation.

In addition, by comparing the three simulations, it appears that the pointing error comes from both estimation errors and mechanical defects, in approximately the same proportion. The error caused by the satellite position estimator is 0.10 degrees RMS. It comes mostly from the SNR and antenna gyroscopes noise. The mechanical defects induce 0.08 degrees RMS. This error is mostly due to backlash.

6. CONCLUSION AND FUTURE WORKS

In this document, a hybrid pointing strategy is described and tested in simulation. The results show acceptable robustness with respect to APS defects like backlash, friction, mechanical compliance, imbalance and sensor imperfections such as noise and drift. In addition, self-induced dither is used, introduced only by the measurement noise, making unnecessary the use of additional dither. Furthermore, no attitude measurement is used. All these characteristics make the strategy presented well suited for low cost SATCOM On The Move applications.

Even if first results are encouraging, several perspectives need to be addressed. The estimator presented here uses two sets of gyroscopes (VG and AG on figure 1). The use of only one set of gyroscopes is currently studied. In addition, a comparison with existing pointing strategies must be done. More precisely, the amount of dither introduced by gyro noise shall be numerically compared with the dither of a Conical Scan.

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