SATCOM ON THE MOVE (SOTM) SYSTEM

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ABSTRACT

This paper provides an overview of the Satcom On The Move (SOTM) system. Antenna servo system requirements for the SOTM have been derived and discussed. Different classes of antennas are discussed, including mechanically steered versus electronically steered with advantages & disadvantages of both. System Design has been discussed in brief. A mathematical model of dc servo motor based antenna control system is developed and step response analysis of the open/closed loop system and unit step response with a PID controller has been analyzed using MATLAB/ Simulink.

Key words: Satcom on the move (SOTM), Servo control, Antenna control system, PID.


1. INTRODUCTION

In today’s scenario Militaries worldwide rely heavily on satellites to fulfill their communications requirements. However since modern warfare is highly asymmetric and mobile modern Military needs Satcom on the move (SOTM). The major push for Satcom on the move came during the Iraq war where both military and broadcaster crews was looking for this application to coordinate war logistics and transmit the news from the Battle zone. An SOTM control system performs the complex task of not only positioning the antenna to the desired angle but also to stabilize the antenna by cancelling out the disturbance caused by motion of the base vehicle.

2. SYSTEM REQUIREMENTS

2.1. Pointing Requirement

SOTM is essentially a satellite antenna with steerable pedestal, RF modules and base-band mounted over a moving platform to establish communications on the move. Ku Band has got the advantage that the size of antenna required is relatively small which is a great advantage
for SOTM as smaller antenna can be easily mounted on the vehicle top. Generally the size of Ku band antenna is less than 1m. The figure below shows the Gain pattern of a typical Ku Band Antenna courtesy of the General Dynamics Ltd.

![Gain pattern](image)

**Figure 1**

As is clear from the figure1 the antenna gain decreases rapidly as the angle from bore sight is increased hence for a good RF Link the control system should keep the antenna main-lobe pointed towards the satellite. Another constraint on pointing is ASI or adjacent satellite interference the side lobes of the antenna have sufficient power to lock on to a satellite if the pointing angle is not correct the side lobe can lock on the target satellite with the main lobe of the antenna pointing towards an adjacent satellite. These two requirements put strict limitations on the antenna pointing. Ku band is 12-18 GHz. Beam width (BW) of an antenna can be calculated by the formula

\[ BW = \frac{70 \times \lambda}{D} \]  

Where \( \lambda \) is the wavelength given by \( \lambda = 0.3/f \) where \( f \) is the frequency in GHz.

D = Diameter of the antenna in meters.

Taking \( f= 15 \) GHz and \( D = 0.6m \) gives \( BW = 2.33^\circ \).

Antenna pointing loss shall not exceed 0.5 dB for systems employing tracking which gives pointing error less than 0.4\(^\circ\). Thus the antenna pointing error \( P \leq 0.4^\circ \).

There are two possible configurations for SOTM one is an Mechanically steerable Dish Antenna (MSDA) and the other is Electronically steerable Array antenna (ESA), it can be partial ESA with one axis (azimuth) mechanically steered or fully ESA which uses an phase shifting network to steer the beam. A brief comparison between the two is given below.

<table>
<thead>
<tr>
<th></th>
<th>MSDA</th>
<th>ESA</th>
</tr>
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</table>
| Mechanical dish has an advantage of mass stabilization thus requiring minimal torques by motor to stabilize which in turn reduces the motor torque and size. | Partially ESA (azimuth axis mechanically steered) has no mass stabilization and requires large motor torques for stabilizing.  
Full ESA does not have this problem. | |
| High Gain values can be achieved | Low Gain thus for higher data rates can be achieved only by operating at much higher power levels. | Generate Significant energy outside of the main lobe thus ASI (adjacent satellite interference) becomes a problem. |
| Energy in side lobes is considerably less compared to ESA | | |
| Simple control algorithms | Complex control algorithms | |
| Economical | Very Expensive | |
| Tracking rate is slow. | Tracking rates are very fast. | |
| Accuracy is not very high. | Very high accuracy. | |
| Size is large, typically around 1m antennas. | Size is very compact. | 

Table 1
In view of these observations one can draw the following conclusions. MSDA seems to be an appropriate and cost effective choice for SOTM unless the demand for accuracy are extremely high & size required is very compact.

2.2. Antenna 2 axis Range

SOTM can be mounted on aircraft, ship or land based vehicle. It uses a 2 axis elevation over azimuth pedestal for antenna orientation (azimuth over elevation pedestal can also be used depending on the requirement). In this paper we focus on land based SOTM and for that we assume Ashok Leyland stallion as the base vehicle for the SOTM and all the calculations will be based considering stallion as the base vehicle and a 2 axis elevation over azimuth pedestal for antenna.

![Figure 2](image)

2.2.1. Elevation axis Coverage

For a fixed base antenna the range of antenna on elevation axis is 0-90°.

The Elevation angle for the satellite antenna is given by

\[ El = \arctan((\cos G \cdot \cos L - 0.1512)/\sqrt{1 - \cos^2 G \cdot \cos^2 L}) \]  

(2)

Where G = difference between satellite orbital position & antenna longitude.

L = latitude of the antenna.

Coordinates of 4 extreme points in India are North-Indira Col (35.66° N 76.79° E), South (Mainland)-Cape comorin (8.08° N 77.53° E), East-Kibithu (28.28° N 97.01° E), West-Sir Creek (23.58° N 68.48° E) considering INSAT-3B (83° E) satellite we compute the look angles. We get minimum elevation as 48.1° and maximum elevation 78.5°. Thus the range of Elevation axis for a stationary antenna should be 48 - 79°. From the specifications of stallion the maximum Gradeability of the Stallion is 30° (ref figure 2). Gradeability is the highest grade a vehicle can ascend while maintaining its speed. It is measured in degrees from the horizontal. Hence we need to add +/-30° to the range, but since +30° can be compensated by the azimuth axis total elevation range becomes

\[ El = 18° \text{ to } 79°. \]

2.2.2. Azimuth axis Coverage

Since the vehicle can take a complete 360 degree turn the azimuth axis range should be

\[ Az = 0° \text{ to } 360°. \]
2.3. Vehicle Dynamics

The stallion has six degrees of freedom, 3 translational and 3 rotational. Consider the satellite to be in Geostationary orbit i.e. 35,786 Km above earth. At such height the translational motion of the vehicle will have very minute effect on the change in antenna look angles. Once the antenna is aligned with the satellite using the GPS coordinates, the vehicle translational motion will not cause the look angles to change very much and thus we can ignore the 3 translational motion equations. The antenna misalignments are caused by 3 rotational motions of the vehicle which are discussed below.

2.3.1. Vehicle Pitch

Since the ground clearance for the stallion is 305mm the maximum vertical step it can climb without damaging the lower chassis is 0.305m. We take it to be 0.3m.

Consider a free fall from the step size of 0.3m.

![Figure 3](image)

Under free fall applying Newton’s equation of motion

\[ S = ut + \frac{1}{2}at^2 \]  

\( S = 0.3\text{m} \)

\( u = \text{initial velocity} = 0 \)

\( a = \text{acceleration due to gravity} = g \)

\( g = 9.8\text{ m/s}^2 \)

\( t = 0.24\text{ sec.} \)

To compute the change in the pitch angle consider figure 4.

![Figure 4](image)
In the figure 4, x is the wheel base of the stallion = 4500mm = 4.5m
y is the step size = 0.3m
Φ is the pitch angle from figure 4
\[ \sin \Phi = \frac{y}{x} \] (4)
hence pitch angle \( \Phi = 3.822^\circ \)
rate of change of pitch angle is \( \frac{\Delta \Phi}{\Delta t} \)
hence the rate of change of pitch angle is 16°/sec. Thus the elevation axis rate should be at least 16 deg/sec or the system will fail to catch the rapid change in the pitch axis of the vehicle. Vehicle Pitch can be compensated by driving the elevation axis.

2.3.2. Vehicle Yaw
The stallion has a minimum turning radius of 18m. Consider figure 5 shown below for vehicle taking a turn.

![Figure 5](image)

Neglecting friction and road banking there are two forces acting on the vehicle
F is the centripetal force acting inwards & W is the weight acting downwards.
\[ F = \frac{mv^2}{R} \] (5)
\[ W = mg \] (6)
D = wheel track, H = height from ground to CG of the vehicle
\[ T1 = F \times H/2 \] (7)
\[ T2 = W \times D/2 \] (8)
For a stable turn \( T2 > T1 \)
Else the vehicle will rollover and topple while taking the turn. Putting the values we get
\[ \frac{mv^2}{R} \times H/2 = Mg \times D/2 \] (9)
Stallion Front track = 2030mm Rear track = 2050mm taking 2050/2 = 1.025m as wheel track and H = 1.5 m and turning radius R = 18m we get
\[ v = 10.979m/sec \]
\[ v = 11m/s. \]
from geometry
\[ S = R \times \theta \] (10)
For azimuth angle to change from 0 to 90° distance covered is given by
s = 18x 90 x 3.14/180 = 28.26 meters at a speed of 11 m/s. Time t required to cover this distance is t = d/s = 2.56 secs. So rate of change of yaw angle is

\[
\frac{\Delta \theta}{\Delta t} = \frac{\theta}{t}
\]

YAW = 90/2.56 = 35.15°/sec.

Hence the antenna control systems should drive the azimuth axis at minimum rate of 36°/sec. Upon loss or blockage of signal the system should reacquire the satellite as quickly as possible which requires elevation axis rate to be as high as possible however systems limitations put limitation on the upper limit. According to DVB S2 standard maximum time of signal loss is given by

\[
T \leq \sqrt{\frac{1.25 \times 107}{R}}
\]

where R is the Data Rate in Mbps. In our case we take R=2 which gives T ≤ 2.5 sec. For maximum travel of azimuth axis from 0-180° in 2.5 sec gives tracking rate of 72 °/s. Assuming it takes 2.5 sec to reach from 0 - 180° then using equation (3) acceleration is ≥ 58 °/sec². Vehicle yaw can be compensated by driving the azimuth axis.

2.3.3. Vehicle Roll

In land based SOTM the typical vehicle roll will be of the order of +/- 5°. This vehicle roll can be compensated by appropriate adjustment in the azimuth & elevation axis. For applications requiring elevation angles nearing 90° the system suffers from a problem called gimbal lock in which for El > 80° the power required by the azimuth motor increases considerably thus making it difficult to compensate even small changes in vehicle roll. In such cases 3 axis gimbals are used to stabilize the antenna where a separate roll axis is used to cancel out the vehicle roll.

3. LOOK UP ANGLES

Consider figure 6, here G is the Global reference frame & V is the Vehicle reference frame.

The standard z-y-x Euler angle representation is used here.

\[
El = \text{atan}(Z/\sqrt{(X^2 + Y^2)})
\]

\[
Az = \text{atan}(-X/Y)
\]

where X, Y & Z are defined as

\[
X = -xp + (xs - xv)cos\alpha cos\beta + (ys - yv)sin\alpha cos\beta - (zs - zv)sin\beta
\]
\[ Y = -\gamma p + (x_s - xv)(\cos \beta \sin \gamma - \sin \gamma \cos \beta) + (y_s - yv)(\cos \gamma + \sin \beta \sin \gamma) + (z_s - zv)\cos \beta \sin \gamma \]  
(15)

\[ Z = -\gamma p + (x_s - xv)(\cos \beta \cos \gamma + \sin \gamma) + (y_s - yv)(\sin \beta \cos \gamma - \cos \gamma) + (z_s - zv)\cos \beta \cos \gamma \]  
(16)

Here
- \( El \) = required elevation angle
- \( Az \) = required azimuth angle
- \((x_s, y_s, z_s)\) = coordinates of satellite
- \((x_v, y_v, z_v)\) = coordinates of the vehicle
- \((x_p, y_p, z_p)\) = coordinates of the pointing mechanism in the vehicle reference frame.
- \( \alpha \) = yaw of the vehicle.
- \( \beta \) = roll of the vehicle.
- \( \gamma \) = pitch of the vehicle.

4. SYSTEM DESIGN

The main design consideration is how to acquire the satellite and then keep tracking it. Broadly there are two approaches to this open loop and closed loop method. The open loop method uses the known position of the satellite to orient the antenna and to reorient the antenna based on its current heading. However achieving high accuracy with this method that relies solely on the Inertial Measurement Unit (IMU) measurements to steer the antenna to the new position is very difficult. Second approach is the closed loop method in which the antenna seeks the orientation that maximizes the receiver signal. This requires mechanical scanning of the antenna across the sky. Examples of mechanical scanning are conical scan and step tracking. A third approach is the Hybrid method which uses both open loop and closed loop method. The antenna is first aligned to the satellite using the open loop method and then the antenna uses closed loop approach i.e. step tracking to track the satellite. Figure 8 shows the block diagram of a SOTM antenna control system where \( AZ \) is the azimuth motor & \( EL \) is the elevation motor. Antenna pointing is done in two stages first stage is tracking which is done through the inner loop. Second stage is stabilization which is the outer loop & uses a 6 DOF Inertial Measurement Unit (IMU) which measures the base vehicle disturbance i.e. roll, pitch & yaw. IMU provides feedback to the ACU (antenna control unit) which compensates the disturbances and computes new values of azimuth and elevation and gives drive signals to the motor driver which in turn drives the AZ and EL motors.

Figure 7 Block diagram of an SOTM antenna control system
We have already derived the antenna servo system requirements and discussed the system design in brief now we develop the mathematical model of the system. Mathematical modeling is done for azimuth axis of the antenna control system. We will derive the transfer function of the azimuth axis drive system and obtain the step response of the both open loop and closed loop system using MATLAB/Simulink. We will further try and improve the system response using a well-tuned PID controller. There are several well-known methods for PID tuning, the PID controller can be tuned using Zeigler Nichols method or any other such methods. PID tuning is beyond the scope of this paper and will not be discussed here. The values of Proportional Gain $K_p$, Integral gain $K_i$ & Derivative Gain $K_d$ for which the system performance is found to be satisfactory are given with the step response plot.

5. MATHEMATICAL MODEL OF A DC SERVO BASED ANTENNA CONTROL SYSTEM & STEP RESPONSE ANALYSIS IN MATLAB/ SIMULINK

![Figure 8](image)

Figure 8

\[ Ev = \text{error voltage} \]
\[ I_a = \text{motor armature current} \]
\[ L_a = \text{armature inductance} \]
\[ R_a = \text{armature resistance} \]
\[ E_b = \text{back emf} \]
\[ J_L = \text{Load Inertia} \]
\[ D_L = \text{Load friction constant} \]
\[ \theta = \text{angular position of motor shaft} \]
\[ T_m = \text{motor torque} \]
\[ K_t = \text{motor torque constant} \]

On the motor side we have

\[ V = I_a R_a + L_a \frac{d(I_a)}{dt} + E_b \quad (17) \]
\[ I_a R_a + L_a \frac{d(I_a)}{dt} = V - E_b \quad (18) \]
\[ \text{error voltage } Ev = V - E_b \quad (19) \]
The error voltage is amplified by the amplifier given by \( K/(S-a) \) so the above equation becomes

\[
1aRa + La \frac{d(Ia)}{dt} = Ev x K / (S - a)
\]  

(20)

Taking laplace transform of above equation

\[
a(S) (Ra + LaS) = Ev(S) x K / (S - a)
\]  

(21)

\[
a(S) = Ev(S) / (Ra + LaS)
\]  

(22)

\[
Tm = Kt x Ia
\]  

(23)

On the load side we have

\[
JL \frac{d^2(\theta)}{dt^2} + DL \frac{d(\theta)}{dt} = Tm
\]  

(24)

Taking laplace transform of the above equation we get

\[
S2JL\theta(s) + S DL\theta(s) = Kt x Ev(S) x K / (Ra + LaS) (S - a)
\]  

(25)

Transfer function of the antenna azimuth axis servo system is \( G(s) = \frac{KKt}{S(S JL + DL)(Ra + LaS) (S + a)} \)  

(26)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
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<tr>
<td>( J_L )</td>
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</tr>
<tr>
<td>( D_L )</td>
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<td>( L_a )</td>
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<td>( R_a )</td>
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</tr>
<tr>
<td>( K )</td>
<td>1000</td>
</tr>
<tr>
<td>( K_t )</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 2 Gives the values of the parameters used for simulation in MATLAB.

The open loop transfer function is given by

\[
G(S) = \frac{500}{S(S+1)(0.45S+8)(S+100)}
\]
Figure 10 Closed loop unit step response.

Figure 11 Closed loop step response with a PID controller $K_p=13.44$, $K_i=0.91$, $K_d=15$

Figure 10 shows the closed loop unit step response of the system. It is observed that the system response is very slow with a settling time of nearly 10 sec and a peak overshoot of nearly 10%. To improve the system performance, a PID controller is used and Figure 11 shows the closed loop unit step response with a PID controller. It is observed that the system response has become faster with settling time of less than 1 sec and also the peak overshoot is reduced to nearly 6%. Thus, with the help of a PID controller, the system performance has improved.

6. CONCLUSIONS

We have discussed SOTM system and derived the antenna servo system requirements for an SOTM. A mathematical model of an servo drive system for the azimuth axis of antenna was developed & step response of the uncompensated and PID compensated systems have been plotted using MATLAB/Simulink. It is seen that the system performance improved using a PID controller with faster system response. We also compared the MDSA & ESA; this has allowed us to draw some conclusions regarding their suitability for SOTM. The future scope involves hardware implementation of the SOTM antenna system in which we will try to stabilize the antenna using a 6 DOF IMU.
REFERENCES

[6] ETSI ITR 102 768 V 1.1.1