Indian National Society for Aerospace and Related Mechanisms
BANGALORE CHAPTER

# E-NEWSLETTER

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## From the Editor

Dear Member,

It gives me immense pleasure to present you with this edition of our E-news letter. The second half of this year was particularly eventful for the members of Spacecraft Mechanisms Group (SMG) at ISAC. The SMG team witnessed excellent on-orbit performance of state of the art motorized deployment mechanism for UHF Tx helix antenna onboard GSAT 7 spacecraft and a new solar panel drive module onboard MOM spacecraft. These are in addition to the nominal on-orbit performance of other conventional mechanisms like solar array/antenna deployment mechanisms onboard IRNSS-1A, GSAT7, INSAT 3D and MOM spacecrafts. All these mechanisms have worked flawlessly in orbit. Totally there were thirteen on-orbit deployments during the year 2013. The editorial committee congratulates the past and present members of Spacecraft Mechanisms Group, ISAC for these excellent achievements.

INSARM Bangalore chapter is putting best possible efforts to appraise our members about the new development in mechanisms. In this regard INSARM, Bangalore Chapter organized one day workshop on 13th September 2013 on "*Electro mechanical drives*" at ISRO Satellite Centre, Bangalore. Sri C. D. Sridhara, President INSARM, Bangalore chapter briefed the audience about the growth and developments of INSARM Bangalore Chapter from inception. Sri. R.K.Srinivasan, Deputy Director, MSA, ISAC addressed about the developments of various mechanisms of SMG. The workshop was inaugurated by Director, ISAC. The programme began with an invited talk on "*Introduction to the electro mechanical drives development in SMG*" by Sri. N.Viswanatha, Group Director, SMG. This was followed by three lectures delivered by Sri. M.H . Ravichandran, Head, Magnetics Section, SSG, IISU, Sri. T.R.Haridas, Group Head, Spacecraft Actuator Electronics Group, IISU and Sri. Baskaran Krishnamurthy Project Leader in Maxon Precision Motor India Private Limited. The seminar was well attended including several INSARM members and appreciated. The abstract of the technical session lectures are presented in this news letter.

Mission involving large number of distributed small satellites involves development of efficient and robust control guidance logic. The article titled *"Formation flying of small satellites using suboptimal MPSP guidance"* presents such an algorithm.

I am happy to inform that the paper presented by our INSARM member Smt. *G. Srividhya* has been awarded best paper for technical oral presentation at International Conference of Robotics Society of India held at Pune. The details are presented in this news letter. The editorial committee congratulates for her achievement.

This news letter is intended to be a platform for the exchange of information regarding the current developments, new ideas and novel concepts in the area of mechanisms and related field through active participation of members. I request all INSARM members to actively contribute technical articles related to mechanisms to enhance the technical value of the e-new letter.

With best regards,

Dr. B.P. Nagaraj
Chief Editor

## CONTENTS



***Quote:***

***"Innovation comes only from readily and seamlessly sharing information rather than hoarding it."***

***By Tom Peters***

# ONE DAY WORKSHOP ON ELECTROMECHANICAL DRIVES

One day workshop on Electromechanical drives was conducted on the 13th September 2013, as a platform for knowledge sharing and discussion forum on the available technologies in the field of electomechanical drives being used in Spacecrafts. This workshop was concentrated upon the design philosophies adopted and application areas of such drives. Enthusiastic participation to the workshop was observed with nearly a packed hall through the sessions. The questions asked from the audience were well taken by the speakers and adequate response depicted the in-depth knowledge of the subject. The workshop was inaugurated by the Dr. S. K. Shivakumar, Director ISAC. Glimpses of the event can be seen in the images below.


**Members on the dice, (Left to Right):** N.Viswanatha, Group Director, SMG, Sri. R.K.Srinivasan, Deputy Director, MSA, ISAC, Dr. S. K. Shivakumar, Director ISAC, Sri C. D. Sridhara, President INSARM, Bangalore chapter, Sri. K.A. Keshava Murthy, General Secretary INSARM, Bangalore chapter

Lighting of Lamp during Inaugural Session

Distinguished Participants of the workshop

Abstracts submitted by each speaker has been included in the subsequent articles

# Stepper Motors

***M. H. Ravichandran, V. T. Sadasivan Achari***
***ISRO Inertial Systems Unit, Trivandrum***

Stepper motors are electromagnetic incremental devices that convert electric pulses to shaft motion (rotation). These motors rotate a specific number of degrees as a respond to each input electric pulse. Typical types of stepper motors can rotate 1.8°, 2.5°, 5°, 7.5°, and 15° per input electrical pulse. Rotor position sensors or sensor less feedback based techniques can be used to regulate the output response according to the input reference command. Stepper Motors are classified in to three types, Variable Reluctance type, Permanent magnet type and Hybrid Stepper Motor. Hybrid Stepper Motor has the advantage of highest torque density and least step angle among the three. In all the three types, torque is proportional to the supply current.

There are two main modes of operation of stepper motors, Start and Stop mode and Slew mode. In start and stop mode, the motor is controlled to settle down after each step before advancing to the next step. The rotational speed will be in the form of pulses that drops to zero at the end each step while the rotor position will be in the form of pulses also but with an increasing steady state value with time. In slewing mode the motor is controlled to rotate at a constant uniform speed without stopping at the end of each step and the rotor position varies linearly with time. The torque speed characteristic of this mode will not be affected by the system inertia because of the constant speed. The performance of stepper motor can be analysed by its static and dynamic characteristics. The characteristics relating to stationary motors are called static characteristics (T-θ and T-I characteristics). The variation of developed torque with rotor position is T-θ characteristics. The maximum of developed torque is holding torque. Detent torque is the maximum load torque that an un-energized stepper motor can with stand without slipping. The variation of the holding torque with excitation is T-I characteristics. The characteristics relating to motors which are in motion or about to start are called dynamic characteristics (Pull in torque, Pull out torque, Maximum starting frequency, Maximum pull out rate and Maximum starting torque). Pull in torque characteristics otherwise called the starting characteristics and refer to the range of frictional load torque at which the motor can start and stop without losing steps for various frequencies in a pulse train. Pull out torque otherwise called slewing characteristics is the maximum load torque that can be applied to bring the motor out of synchronism.

The most useful information in selecting a stepper motor is the torque vs. stepping rate curve. In addition to that, the other parameters which are important are Number of steps per revolution, Starting torque of motor when powered with rated voltage, Maximum slew rate, Motor torque at maximum slew rate (pull-out torque), Maximum ramping slope, Motor time constants, Motor natural frequency, Motor size (dimensions of poles, stator and rotor teeth, air gap and housing, weight, rotor moment of inertia) and Power supply capacity (voltage and power)

# Stepper Motor Drives and Control

*T.R.Haridas*
*ISRO Inertial Systems Unit, Trivandrum*

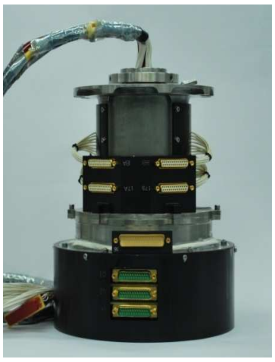
Stepper motor is a Brushless, Synchronous Electric Motor which converts electrical pulses into discrete mechanical movements. Stepper motors provide a means for precise positioning and speed control without the use of feedback sensors. The rotor of the motor produces torque from the interaction between the magnetic field in the stator and rotor. The strength of the magnetic fields is proportional to the amount of current sent to the stator and the number of turns in the windings.

The unique features of Stepper Motor are that they are brushless and hence very reliable, Load independent, Open loop positioning, Holding torque and excellent response to start-up, stopping and reverse. Among the different types of stepper motor viz. Variable reluctance, Permanent magnet and Hybrid type, the Hybrid type is widely used because of its small step length and higher torque to volume ratio.

Stepper motors are operated in Unipolar or Bipolar mode with different types of stepping schemes viz. half stepping, full stepping and Micro-stepping. In Micro-stepping drive, the currents in the windings are continuously varied to break up one full step into many smaller discrete steps.

Stepping motors are normally operated without feedback and may suffer from loss of synchronization. In the open loop control, the Hybrid Stepper Motor often use about 50% of its nominal torque since large torque reserve is required to overcome any load variation. This introduces large overshoot, resonance and torque ripple problems. Besides, if fast excitation changes are applied, the stepper motor can lose steps and this would result in a permanent error causing it to lose its stability and synchronization. For these limitations a closed loop controller is of utmost importance for high performance applications.

There are different closed loop control techniques to overcome the Loss of synchronization. Control algorithm implementations which allow a stepping motor to operate effectively in open-loop mode as long as it remains synchronized, and allow it to recover from loss of synchronization following a disturbance, are available. With this, Stepper motor can be controlled to rotate with constant acceleration or deceleration. The algorithm can be implemented in microcontroller, DSP or FPGA.



INSAT type SADA

SADA Drive Control Electronics

# Coreless Permanent Magnet DC motor technology

*Baskaran Krishnamurthy*
*Maxon Precision Motor India Private Limited*

Coreless permanent magnet DC motors are increasingly finding its use in many aerospace applications like air conditioning equipment's, brake flap adjustment, seat and display adjustment, Flight recorders, solar sail adjustment, Radar Systems, Luggage Hatch equipment's, Autopilots etc., Coreless motors – both brushed and brushless – are also widely used in rovers of missions like Curiosity, Spirit and Opportunity. They are also used in other satellite applications like Sentinel 3.

## 1. Coreless brushed DC motors

Coreless brushed DC motors has a different design to that of conventional DC motors. In conventional motors winding is wound around an iron core, whereas in coreless motors winding is of self-supporting type and Iron core is absent. Permanent magnet is along the housing surrounding the winding in conventional DC motors, whereas in coreless DC motors permanent magnet is placed in the centre of the motor near the shaft. However, shaft and permanent magnet are not connected. Coreless DC motors have many advantages over conventional DC motors. Zero cogging, Zero iron losses, Compact design, low inductance and hence longer life are some of the advantages of coreless DC motors.

Stator consists of permanent magnet and housing with flanges. The housing is made of magnetically conducting material which guides the magnetic field lines generated from North Pole towards South Pole. Newer and stronger permanent magnets are being discovered and typically Neodymium Ferrite boron magnet type is used in coreless motors. These are strong magnets which help in producing strong motors. Samarium Cobalt type magnet is another popular choice for coreless DC motor manufacturers.

Rotor consists of winding and commutator plate fixed with the shaft. Each winding is made of copper, surrounded by an insulation material which is again surrounded by thermo plastic solvent. This is subjected to high temperature and pressure. At higher temperatures, thermo plastic solvent gasses out and the shape is thereby formed with high pressure. Eventually, we get a very strong winding in this process.

Fleming's left hand rule helps us understand the motor principle and also explains the torque generation. Produced torque is directly proportional to current and is dependent on the design constant torque constant. Speed is directly proportional to voltage applied and is dependent on the design constant speed constant.

Commutator bars helps in switching the current to different winding according to the magnet position and hence we get continuous power from the motor. Odd number of commutator bars helps reduces the torque ripple. Graphite brushes are widely used in Aerospace applications, though precious metal brushes are also used in some industrial applications. Ball bearings are widely used in Aerospace applications, though there is an option of sleeve bearings for the motors. A general statement on life of the motor is not possible and it depends on many factors like load on shaft, temperature, humidity, duty cycle etc.

## 2. Coreless brushless DC motors

Coreless brushless DC motors or EC motors are similar to brushed DC motors in principle of operation. Differences are in stator and rotor. In brushless DC motors, permanent magnet forms the rotor and winding is placed in the stator. Another difference is the absence of brushes. Instead of brushes, digital hall sensors are present to perform the function of brushes. Additional electronics are required to run the EC motors. Main advantages when compared to brush motors are higher speeds and higher life.

Commutation can be done in two types in BLDC or EC motors. One is block commutation and the other is sine commutation. Block commutation is performed only with the help of 3 hall sensors placed 120 degree apart from each other. Sine commutation is performed with both the hall sensor signals and encoder signals. In block commutation, commutation happens once in every 60 degrees whereas in sine there are more commutation points and hence smoother operation even at low speeds.

## Speakers of the workshop on Electomechanical Drives


Shri N Viswanatha, *"Introduction to the electro mechanical drives development in SMG"*

**Sri. Ravichandran M.H** *"Stepper motor design and applications"*

**T.R.Haridas** *"Stepper motor drives and control"*

**Baskaran Krishnamurthy** *"Sizing and selection of high precession DC motors"*

# FORMATION FLYING OF SMALL SATELLITES USING SUB-OPTIMAL MPSP GUIDANCE

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### *1. Introduction and Motivation*

Missions involving conventional large satellites are usually quite expensive to design, fabricate, launch and operate as they require massive investment on infrastructure and support system. In addition, in general they require large control forces and moments for their trajectory and attitude corrections, which has been an important factor for the limited life span of the satellites as well. Consequently, an emerging trend across the globe is to have missions involving many small, distributed and largely inexpensive satellites. Due to their limited size and weight, small satellites cannot achieve many missions on their own. Hence, there is a strong need to have missions involving multiple small satellites. In view of this, Satellite Formation Flying (SFF) has become popular because of the potential to perform coordinated missions enhancing their overall capability substantially. One of the key issues in successful small satellite missions is to come up with efficient and robust control and guidance logics. In fact, some interesting control and guidance strategies for reconfiguration and formation flying have been reported in the recent literature. For example, in the framework of optimal control, Vadali et al. [1] have proposed an optimal control theory based solution for the problem of formation flying of satellites. Ahn et al. [2] have developed a robust periodic learning control for trajectory keeping in satellite formation flying under time periodic influence of external disturbance such as gravitational perturbation, solar radiation pressure and magnetic field. Park et al. [3] have developed SDRE solution for SFF reconfiguration and station keeping. Irvin [4] has carried out some interesting comparison studies for various linear and non-linear control technique applied to SFF such as LQR, SDRE and sliding mode control. In ideal case satellite should solve the complete nonlinear local problem and should collectively develop a globally stabilizing distributed controller with good performance from local controllers. In reference [5], a distributed LQR solution for dynamically identically decoupled systems for LTI systems has been proposed.

### 2. Objective

Even though many ideas have been reported in the literature, there still exists vast scope for further research. For example, many algorithms use the 'linearized dynamics', which inherently truncates the system behaviour and hence result in only approximate solution. Similarly some other techniques do not rely on the powerful optimal control theory, which provides a natural platform for trajectory optimization. This paper is excerpt of the of the work presented by G. Joshi and Radhankant Padhi [11], the main aim of the research carried out is primarily to develop a suboptimal guidance logic for formation flying of small satellites based on recently developed MPSP controller, refer R.Padhi and M.Kothari [6], O. Halbe and R. Padhi [7].

### 3. Model Predictive Static Programming (MPSP)

A general discrete nonlinear system is considered here, the state dynamics and output equation of which are given by

$$X_{k+1} = F_k\left(X_k, U_k\right) \tag{1}$$

$$Y_k = H\left(X_k\right) \tag{2}$$

where $X \in R^n, U \in R^m, Y \in R^p$ and $k = 1, 2, \ldots, N$ are the time steps. The primary objective is to come up with a suitable control history $U_k$ , $k = 1, 2, \ldots, N-1$, so that the output at the final time step $Y_N$ reaches a desired value $Y_N^*$. In addition, the aim is to achieve this task with minimum control effort.

For the technique presented here, one needs to start from a guess history of the control solution. With the application of a guess history, however, the objective is not expected to be met. Hence, there is a need to improve this solution. To proceed with the mathematical development, we first define the error in the output as $\Delta Y_N \triangleq Y_N - Y_N^*$. Next, assuming small error approximation we write

$$\Delta Y_N \approx dY_N = \left[\frac{\partial Y_N}{\partial X_N}\right] dX_N \tag{3}$$

However from Eq.(1), we can write the error in state at time step $k+1$ as

$$dX_{k+1} = \left[\frac{\partial F_k}{\partial X_k}\right] dX_k + \left[\frac{\partial F_k}{\partial U_k}\right] dU_k \tag{4}$$

where $dX_k$ and $dU_k$ are the error of state and control at time step $k$ respectively. Expanding $dX_N$ in terms of the errors in state and control at time step $N-1$ as in Eq.(4) and substituting it in Eq.(3), one gets

$$dY_N = \left[\frac{\partial Y_N}{\partial X_N}\right]\left(\left[\frac{\partial F_{N-1}}{\partial X_{N-1}}\right] dX_{N-1} + \left[\frac{\partial F_{N-1}}{\partial U_{N-1}}\right] dU_{N-1}\right) \tag{5}$$

Similarly, $dX_{N-1}$ can be expanded in terms of $dX_{N-2}$ and $dU_{N-2}$, $dX_{N-2}$ can be expanded in terms of $dX_{N-3}$ and $dU_{N-3}$ and so on. Continuing the process until $k = 1$ one can write

$$dY_N = A\, dX_1 + B_1 dU_1 + B_2 dU_2 + \cdots + B_{N-1} dU_{N-1} \tag{6}$$

where

$$\begin{aligned} A &\triangleq \left[\frac{\partial Y_N}{\partial X_N}\right]\left[\frac{\partial F_{N-1}}{\partial X_{N-1}}\right]\cdots\left[\frac{\partial F_1}{\partial X_1}\right] \\ B_{N-1} &\triangleq \left[\frac{\partial Y_N}{\partial X_N}\right]\left[\frac{\partial F_{N-1}}{\partial U_{N-1}}\right], \quad B_k \triangleq \left[\frac{\partial Y_N}{\partial X_N}\right]\left[\frac{\partial F_{N-1}}{\partial X_{N-1}}\right]\cdots\left[\frac{\partial F_{k+1}}{\partial X_{k+1}}\right]\left[\frac{\partial F_k}{\partial U_k}\right] \quad \text{for } k = N-2, \ldots, 1 \end{aligned} \tag{7}$$

Since the initial condition is specified, there is no error in the first term. Hence $dX_1 = 0$ and Eq.(6) reduces to

$$dY_N = B_1 dU_1 + B_2 dU_2 + \cdots + B_{N-1} dU_{N-1} = \sum_{k=1}^{N-1} B_k dU_k \tag{8}$$

Sensitivity matrices $B_k, k = 1, \cdots, (N-1)$ are computed "recursively", which leads to a substantial saving of computational time. Along with the constraint in Eq.(8), the aim is to minimize the following performance index.

$$J = \frac{1}{2}\sum_{k=1}^{N-1}\left(U_k^0 - dU_k\right)^T R_k \left(U_k^0 - dU_k\right) \tag{9}$$

where $U_k^0,\ k=1,\cdots,(N-1)$ represents the previous control history solution and $dU_k$ is the corresponding error in the control history at time step $k$. Here $R_k > 0$ (a positive definite matrix) is the weighting matrix at time step $k$, which needs to be chosen judiciously by the control designer. The selection of such a performance index is motivated by the fact that we are interested in finding a $l_2$-norm minimizing control history, since $(U_k^0 - dU_k)$ is the updated control value at time step Equations (8) and (9) formulate an appropriate constrained static (parametric) optimization problem. Using static optimization theory refer Kirk, D. E [8], the augmented cost function is given by

$$\bar{J} = \frac{1}{2}\sum_{k=1}^{N-1}\left(U_k^0 - dU_k\right)^T R_k \left(U_k^0 - dU_k\right) + \lambda^T \left(dY_N - \sum_{k=1}^{N-1} B_k dU_k\right) \tag{10}$$

where, $\lambda$ is a Lagrange multiplier (ad-joint variable). Using the necessary conditions of optimality for $k=1,\ldots,(N-1)$ one can arrive at the control history update as

$$dU_k = -R_k^{-1} B_k^T A_\lambda^{-1}(dY_N - b_\lambda) + U_k^0 \tag{11}$$

where, $$A_\lambda \triangleq \left[-\sum_{k=1}^{N-1} B_k R_k^{-1} B_k^T\right], \quad b_\lambda \triangleq \left[\sum_{k=1}^{N-1} B_k U_k^0\right]$$

The updated control at time step $k=1,\cdots,(N-1)$ is

$$U_k = U_k^0 - dU_k = R_k^{-1} B_k^T A_\lambda^{-1}\left(dY_N - b_\lambda\right) \tag{12}$$

An important point to note is that, unlike the dynamic optimization theory, the costate (adjoint) variable considered here $\lambda$ is a static variable and not a function of time. In addition to this, the fact that the necessary sensitivity matrices can be computed recursively, termination of the algorithm can happen at output convergence etc. are the main reasons for the computational efficiency. More details about this recently-developed technique with various applications can be found in R.Padhi and M.Kothari [6], O. Halbe and R. Padhi [7].

***4. System Dynamics***

In satellite formation flying mission, relative positions between satellites are important, hence the problem formulation is considered in the relative coordinate system with respect to the chief satellite. For this purpose a non-inertial reference frame centred and moving along with chief satellite is used (which is commonly known as the Hills frame) refer G. W. Hill [9], W. H. Clohessy and R. S. Wiltshire[10]. Frame definition is as follows unit vector $\hat{e}_x$ is along to the local radius vector from the centre of earth, $\hat{e}_z$ along orbital angular momentum and $\hat{e}_y$ is cross product of above two. The nonlinear equation of relative motion of deputy satellite defined in Hill's reference frame is as follows.

$$\begin{pmatrix} \ddot{x}-2\dot{v}\dot{y}-\ddot{v}y-\dot{v}^2x+\frac{\mu}{\gamma}x+\frac{\mu}{\gamma}r_c-\frac{\mu}{r_c^2} \\ \ddot{y}+2\dot{v}\dot{x}+\ddot{v}x-\dot{v}^2y+\frac{\mu}{\gamma}y \\ \ddot{z}+\frac{\mu}{\gamma}z \end{pmatrix} = \begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix} \quad (13)$$

Where $x$, $y$ and $z$ are state variables to describe relative position vector $\vec{\rho}$. The terms $a_x$, $a_y$ and $a_z$ are applied control accelerations in three axis $\hat{e}_x$, $\hat{e}_y$ and $\hat{e}_z$ respectively. The terms $a_x$, $a_y$ and $a_z$ can also include the external perturbation forces such as gravitational perturbation due to non-spherical earth, atmospheric drag and solar radiation pressure. For results presented in this paper, only $J_2$ perturbation forces are considered. In Eq.(13), $\mu = GM = 398601\ \text{km}^3/\text{s}^2$ is gravitational parameter, where G is universal gravitational constant, M is mass of earth , $\nu$ is the true anomaly, $\gamma = |\vec{r}_c + \vec{\rho}|^3$ and $\vec{r}_c$ is radius vector of the chief satellite.

MPSP control method needs the nonlinear equations to be re-written in discretized form, where the states are three relative position and three relative velocities of deputy satellite with respect to chief satellite i.e.

$$[x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6]^T = [x \quad \dot{x} \quad y \quad \dot{y} \quad z \quad \dot{z}]^T$$

Euler equation of motion is used to discretize the nonlinear equation of motion of deputy satellite.

$$\begin{aligned} X_{k+1} &= F(X_k, U_k) \\ F(X_k, U_k) &= X_k + \Delta t . f(X_k, U_k) \end{aligned} \quad (14)$$

Where $f\left(X_k, U_k\right)$ is given as

$$f(X_k, U_k) = \begin{bmatrix} x_{2k} \\ 2\dot{v}_k x_{4k} + \ddot{v}_k x_{3k} + \dot{v}_k{}^2 x_{1k} \ldots \\ -\frac{\mu}{\gamma_k} x_{1k} - \frac{\mu}{\gamma_k} r_{ck} + \frac{\mu}{r_{ck}^2} + u_{1k} \\ x_{4k} \\ -2\dot{v}_k x_{2k} - \ddot{v}_k x_{1k} + \dot{v}_k{}^2 x_{3k} \ldots \\ -\frac{\mu}{\gamma_k} x_{3k} + u_{2k} \\ x_{6k} \\ -\frac{\mu}{\gamma_k} x_{5k} + u_{3k} \end{bmatrix} \quad (15)$$

Where,

$$X_k = [x \quad \dot{x} \quad y \quad \dot{y} \quad z \quad \dot{z}]^T = [x_{1k} \quad x_{2k} \quad x_{3k} \quad x_{4k} \quad x_{5k} \quad x_{6k}]^T$$

and $U_k = \begin{bmatrix} a_x & a_y & a_z \end{bmatrix}^T = \begin{bmatrix} u_{1k} & u_{2k} & u_{3k} \end{bmatrix}^T$ are state and control respectively at time step $k$. RK-4 method is used for propagation of state trajectory, and to enhance the computational efficiency the sensitivity matrices on those grid points are computed using Euler integration formula.

Partial differentials of function $F(X_k, U_k)$ with respect to $X_k$ and $U_k$, partial derivative of output $Y_k$ with respect to $X_k$ are evaluated for calculating the control update using MPSP method. The above said partial derivatives are evaluated from discretized system dynamics. The time step $\Delta t$ for Euler discretization is taken as 1sec. Using these partial derivatives evaluated at each grid points, the sensitivity matrices $B_k$'s are evaluated using (7) and control is updated over previous control values using equation (12).

### 4.1 Problem Objective

The objective of the problem statement is to form the formation or to reconfigure the formation flying of satellites to the desired orbit. The Deputy satellite is initially in an orbit around the earth with initial formation separation distance of $0.5km$. It is desired to raise the orbit of deputy satellite and put it in new formation with spatial separation of $1.5km$. Refer section “Simulation Studies” for detail initial and final orbital conditions considered for the problem statement. The objective of the problem is to minimize the control effort required to reach the new orbit, but at the same time, deputy satellite should achieve the position and velocity of the new orbit accurately. Mathematically we can put the problem objectives as follows.

The main objective here is to minimize the terminal position error, i.e. $\begin{bmatrix} x_1 & x_3 & x_5 \end{bmatrix}^T \rightarrow \begin{bmatrix} x_1^* & x_3^* & x_5^* \end{bmatrix}^T$ at $t = t_f$. However, since the velocity components should also match with the desired orbital parameters, one can also impose $\begin{bmatrix} x_2 & x_4 & x_6 \end{bmatrix}^T \rightarrow \begin{bmatrix} x_2^* & x_4^* & x_6^* \end{bmatrix}^T$ at $t = t_f$, where $\begin{bmatrix} x_2^* & x_4^* & x_6^* \end{bmatrix}^T$ are the corresponding desired orbital velocity parameters at the position $\begin{bmatrix} x_1^* & x_3^* & x_5^* \end{bmatrix}^T$. The error in the output “$dY_N$” is evaluated as follows $dY_N = Y_N - Y_N^*$ where $Y_N^*$ is the desired state vector.

Aim is to compute the control command $U_k$, where $k = 1, \ldots, (N-1)$ so that $dY_N \rightarrow 0$. To achieve this objective, the coefficients $B_1$ to $B_{N-1}$ are evaluated using equation and finally the control command is updated using

### 5. Simulation Studies

In this exercise, the results presented are for circular chief satellite orbit, $10,000km$ radius vector. The initial conditions (i.e. orbital parameters) of deputy satellite for formation flight are considered as follows $\begin{bmatrix} \rho & a & \theta & b & m & n \end{bmatrix} = \begin{bmatrix} 0.5km & 0 & 45^0 & 0 & 1 & 0 \end{bmatrix}$ where “$\rho$” is radial separation in 3d plane with respect to chief satellite in Hills reference frame, “a” and “b” is centre offset of ellipse traced by deputy satellite with respect to chief satellite, $\theta$ is angle of satellite position vector with respect to chief satellite velocity vector, “m” and “n” are the slopes of the line formed by the rotation about the minor and major axis respectively. Final orbital conditions are as follows $\begin{bmatrix} \rho & a & \theta & b & m & n \end{bmatrix} = \begin{bmatrix} 1.5km & 0 & 60^0 & 0 & 1.5 & 1 \end{bmatrix}$. Exogenous “$J_2$” perturbation effects are considered for the formation flying results presented in this paper. For the details of state dependent modelling of the “$J_2$” component refer Park et al. [3]. The guess controller for MPSP SFF problem is obtained through LQR solution approach. The infinite time horizon problem is considered with linearized model. The details of the linear model of SFF and LQR control details can be found in [11]

**6. Results**

Figure 1 shows in 3D orbit transfer from the initial formation to new commanded formation trajectory for circular chief satellite orbit. MPSP trajectory is significantly different from the initial guess (LQR trajectory). MPSP solution tries to minimizes the control and achieve the final states as hard constraints. Five iterations are carried out and corresponding position and velocity error for LQR and MPSP solution methods are shown in the Fig 3 and 4 respectively. MPSP numerical simulation is stopped once the specified error criterion of $\%\rho_{error} < 0.5\%$ is met. Figure 2 gives details of the guess control used for MPSP iteration and MPSP control after 5 iterations. MPSP control poses the terminal constraints as hard constraints and attains the terminal constraints with much lower error tolerance, meanwhile MPSP control also ensures to minimize the control effort required to reach the desired orbit. Hence the control profile of the MPSP controller is significantly different compared to the initial guess LQR controller.

**7. Conclusion**

This paper concisely presents a suboptimal controller experimented with satellite formation flying mission reported in the paper by G Joshi and R. Padhi [11]. The final conditions have been put as hard conditions, because of which the solution turns out to be highly accurate in ensuring the desired orbit for the deputy satellite. MPSP guidance achieves the objective with tighter tolerance and with lesser amount of control usage. It was also reported in [11] that the proposed MPSP guidance is computationally efficient and hence can possibly be used on-board the deputy satellites.

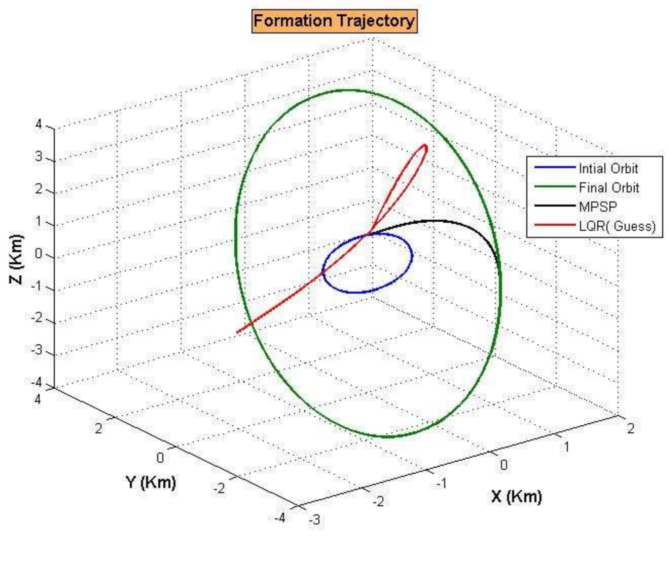


Fig 1: Formation Trajectory plot for guess control (LQR) and MPSP control

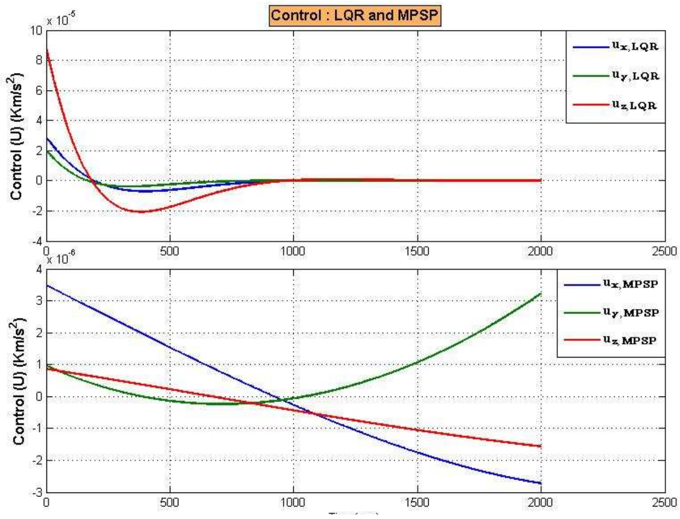


Fig 2: Control history for guess control (LQR) and MPSP.

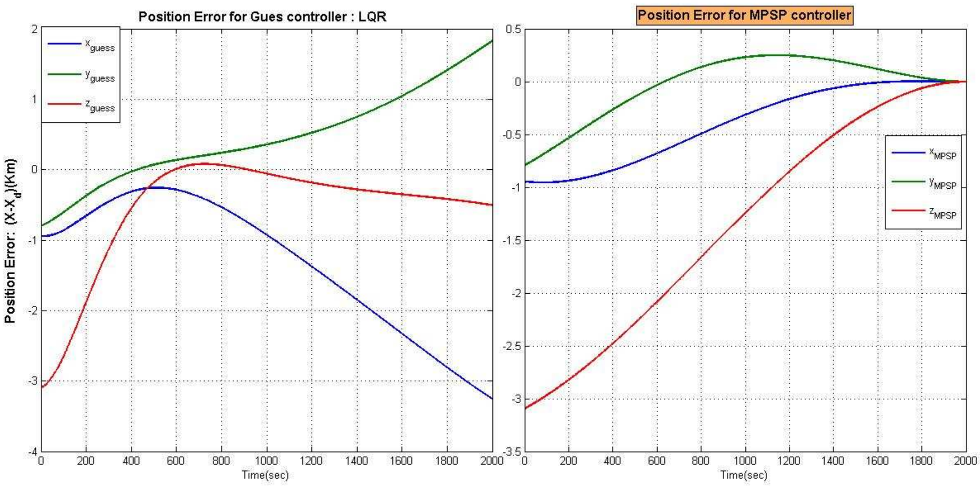


Fig 3: Formation trajectory position error for guess control (LQR) and MPSP control.

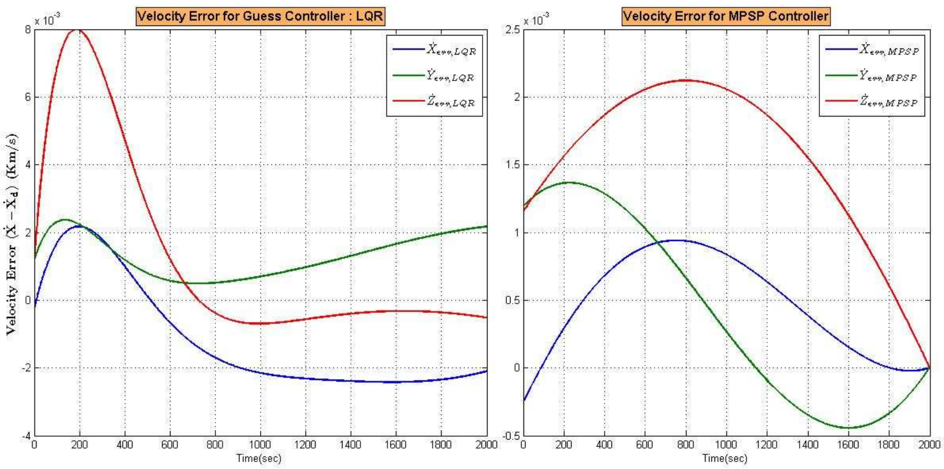


Fig 4: Formation trajectory velocity error for guess control (LQR) and MPSP control.

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