

A Swarm Architecture for Small Satellites Pointing towards Common Targets

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Abstract:

This paper proposes a leader-follower architecture for coordinating a swarm of satellites to observe stationary targets on the Earth's surface. Such a strategy uses the intersection of the line of sight of the distributed sensors as a key parameter to reconfigure and reorient the swarm satellites. Follower satellites receive the goal pointing and position of the leader satellite, to then autonomously calculate the required pointing direction to detect and observe the same targets. The performance of handling uncertainties due to communication delays on the pointing and position goals of the swarm is assessed and compensated via a Smith-like predictor. Simulation results demonstrate the viability of the proposed methodology for a typical small satellite swarm scenario.

1.INTRODUCTION

Distributing sensors among several satellites flying in formation can provide richer data of the observed land that can be used for 3D mapping of events such as natural disasters, farmland irrigation and climate change effects. The data quality is dependent on the coordinated pointing of the satellites towards a common target. Specific applications require fast re-orientation of several satellites to observe multiple target zones near each other on the Earth. Some specific applications require a fixed baseline distance among the observing sensors. This can pose a difficult constraint to satisfy due to the evolving relative dynamics of each satellite. Such challenges are important also for military applications such as 3D mapping of active warzones which is addressed by the NATO SPS project Fedlabs [1].

This paper presents a leader-follower control architecture that allows for the coordination of the relative position and attitude of multiple small satellites to point towards selected targets, so that multi-perspective imaging of the same target can be performed. The architecture allows for compensation of inter-satellite communication delays for sharing common and swarm coordination information.

The problem of pointing coordination among formation flying spacecraft has been addressed many times in the past, with most architectures using perfect knowledge of the target's inertial position to provide target attitudes [2, 3, 4, 5]. Compared to the existing literature, our approach allows for the target position to only be defined by the leader,

reducing complexity and decreasing satellite reorientation time. This can be done because each follower is reliant on information coming from the leader only. Communication delays can lead to inaccuracies in the goal-pointing vector, which might compromise the system's performance. The presented architecture accounts for and compensates for these delays among satellites, reducing this inaccuracy.

The scenario under consideration in this paper assumes 3-satellite formation with following concept of operation: after target detection, the leader sends information about its attitude and position to the followers, along with a flag indicating whether it has a line of sight with a target. The followers use this information to calculate how they should point to observe the target. Using this information, the satellites create a ‘stereo’ formation with one follower in front of the leader and the other behind it, with the distance between each follower and the leader being equal, as shown in Figure 1.

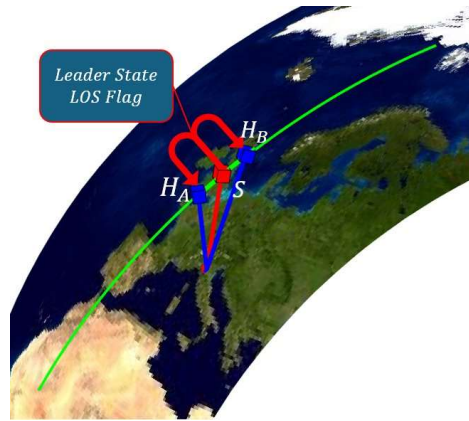


Figure 1 - Data sent from Leader to Follower Satellites

In particular, this paper describes the selected leader-follower architecture, describing the procedure for defining the followers' pointing direction given only the attitude and position of the leader, while predicting the leader's true position and attitude by accounting for communication delays between satellites.

The remainder of this paper will be laid out as follows: Section 2 details the scenario modelling, including frame definitions, calculations of the goal attitude and position for the followers. An overview of the coordination architecture is provided in Section 3, along with the strategy for compensating for the communication delays. The obtained results in an Earth Observation scenario are discussed in Section 4. A conclusion section outlines the preliminary results achieved and future work planned for this study.

2. SCENARIO MODELLING

This section describes the assumptions and the procedure for calculating the position and pointing goals of the follower satellites given the relative state with respect to the leader. The procedure assumes that the satellites are in a near-circular orbit and the attitude actuation allows for a re-orientation of the platforms, also considering saturation torques. The following subsection explains how to obtain the goal relative position that needs to be achieved by the follower once the leader detects the target. After that, a procedure for calculating the goal pointing attitude for the followers is outlined in Section 2.2. These

two procedures will be then used and implemented into the architecture shown in Section 3.

2.1. Relative Position

The followers must have their goal position defined in relative coordinates with respect to the leader. An easy way to do this is to define the orbital arc distance between the leader and follower before converting it to a common Local Vertical Local Horizontal (LVLH) frame. The goal separation of the follower's controller is defined in terms of the arc separating the leader and follower, ΔS , as shown in Figure 2. Given the leader's orbital radius, r_s , this goal can be defined in terms of separation angle, θ .

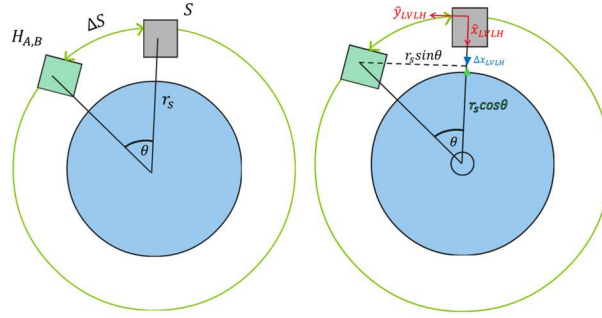


Figure 2 – Left: Leader & Follower Separated by ΔS . Right: LVLH Components of Follower Separation Goal.

θ is calculated by rearranging the equation for the length of an arc as shown in equations 2-1 and 2-2, where D and R represent the diameter and radius of the leader's orbit respectively.

$$\Delta S = \frac{\theta}{2\pi} \pi D \quad 2-1$$

$$\theta = \frac{2\Delta S}{D} = \frac{\Delta S}{R} \quad 2-2$$

The components of the separation are then defined in the LVLH frame by using trigonometry on the left of Figure 2 to get the breakdown on its right. Equations 2-3 and 2-4 then give the following relations by using vector addition and subtraction.

$$\Delta y_{LVLH} = r_s \sin \theta \quad 2-3$$

$$\Delta x_{LVLH} = r_s \cos \theta - r_s = r_s (\cos \theta - 1) \quad 2-4$$

2.2. Point of Interest Pointing Frame for Follower

The pointing attitude of the follower satellite is derived in the LVLH frame due to the follower satellite's relative position, $\delta \mathbf{r}$, being defined in the LVLH frame as shown in Figure 3. With the point S being the centre of mass (CoM) of the leader, H being the CoM

of the follower, $\mathbf{r}_{PS}$ being the pointing vector between S and the target P and $\mathbf{r}_{PH}$ being the pointing vector H to the target P.

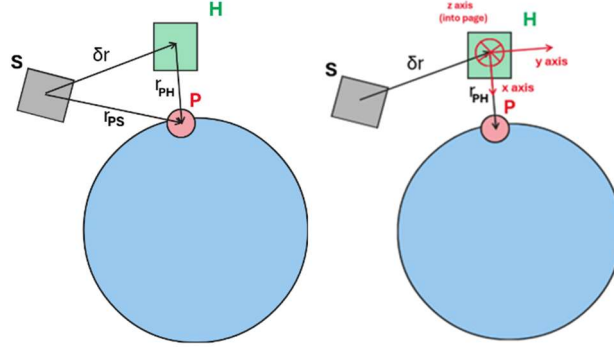


Figure 3 – Left: Follower Point of Interest Pointing Vector Derivation. Right: Follower's Pointing Frame.

As the leader communicates its position and attitude to the follower, $\mathbf{r}_{PS}$ and $\delta \mathbf{r}$ are known. An expression for $\mathbf{r}_{PH}$ can then be defined as follows:

$$\mathbf{r}_{PH} = \mathbf{r}_{PS} - \delta \mathbf{r} \quad 2-5$$

$\mathbf{r}_{PH}$ is then normalised to define the $\hat{\mathbf{x}}_{PH}$ axis of the follower pointing frame as shown in equation 2-6, while the $\hat{\mathbf{z}}_{PH}$ axis is defined as perpendicular to the plane made by $\mathbf{r}_{PH}$ and the $\delta \mathbf{r}$, giving the expression in equation 2-7. The $\hat{\mathbf{y}}_{PH}$ axis completes the right-handed triad.

$$\hat{\mathbf{x}}_{PH} = \frac{\mathbf{r}_{PH}}{|\mathbf{r}_{PH}|} \quad 2-6$$

$$\hat{\mathbf{z}}_{PH} = \frac{\mathbf{r}_{PH} \times \delta \mathbf{r}}{|\mathbf{r}_{PH} \times \delta \mathbf{r}|} \quad 2-7$$

$$\hat{\mathbf{y}}_{PH} = \hat{\mathbf{z}}_{PH} \times \hat{\mathbf{x}}_{PH} \quad 2-8$$

An error quaternion, $\mathbf{q}_{err}$, is defined between the pointing frame defined by these axes and the follower's body frame, which is used as the controller's error input. Details of the $\mathbf{q}_{err}$ derivation are in Section 3.1.2

3.FOLLOWER CONTROL ARCHITECTURE

This section covers the control architectures logic and control strategy to achieve the goal position and goal pointing attitude. The control architecture is centralised around whether the leader is within Line of Sight (LoS) of a target or not. If no target is in sight, the leader and followers will enter a standby mode to maintain communication reliability. If a target is detected, the leader will begin to point at the target and broadcast its state to the followers. As shown in Figure 4, if no target is in sight, the leader will point nadir while setting its LoS flag to zero, communicating to the followers to point towards the leader to maintain communication. If a target is detected, the leader will begin to point at the target and set its LoS flag to 1, communicating to the followers a target is in sight. The followers will begin to receive the leader state, which is offset with respect the leader state, due to

process and communication delays. Such an offset can be corrected by using delay compensation techniques to get an estimate of the leader's current state. With this information the followers calculate their position and pointing goals as described in Section 2.1 and 2.2.

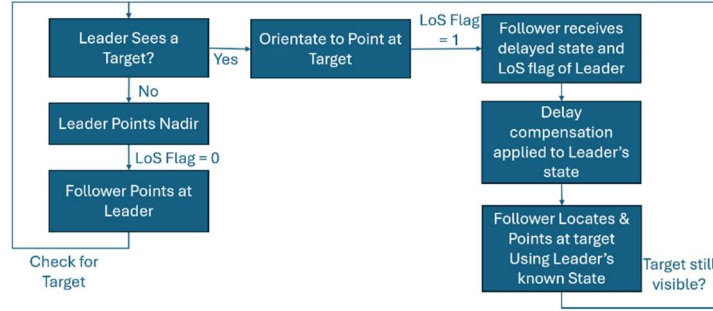


Figure 4 - Flowchart of the Control Architecture

3.1.1. Position Controller

A LQR controller is used to control the position of the satellite in the simulator [6] with CW equations used to linearise the satellites relative dynamics [7]. The LQR controller minimises a cost function shown in equation 3-1, with $\mathbf{Q}$ being a 6x6 diagonal error cost matrix and $\mathbf{R}$ being a 3x3 diagonal actuation cost matrix.

$$J = \int_0^{\infty} \mathbf{x}^T(t) \mathbf{Q} \mathbf{x}(t) + \mathbf{u}^T(t) \mathbf{R} \mathbf{u}(t) dt \quad 3-1$$

$\mathbf{x}(t)$ is the satellite's linear state vector relative to the goal state composed of relative position and velocity in the LVLH frame, while $\mathbf{u}(t)$ is the force applied to the satellite through the thrusters.

The controller produces as an output a control law that minimises the value of the cost function in equation 3-1, following a procedure as outlined in [6].

3.1.2. Attitude Controller

The attitude controller uses the error quaternion, $\mathbf{q}_{err}$, calculated by converting the direction cosine matrix, $\mathbf{T}_{BP}$, that describes the transformation from the body frame, $\mathbf{B}$, to the pointing frame, $\mathbf{P}$, into a quaternion. This matrix is calculated using equation 3-2.

$$\mathbf{T}_{BP} = \mathbf{T}_{BI} \mathbf{T}_{IP} \quad 3-2$$

where $\mathbf{T}_{BI}$ is the transformation from the inertial frame, $\mathbf{I}$, to the body frame and $\mathbf{T}_{IP}$ is the transformation from the pointing frame to the inertial frame. The controller feeds back the vectorial part of the error quaternion as defined in equation 3-3.

$$\mathbf{e}(t) = [q_x, q_y, q_z]^T \quad 3-3$$

The PD controller takes $\mathbf{e}(t)$ and calculates the moment required in the body frame to correct the error.

$$\mathbf{u} = \mathbf{K}_p \mathbf{e}(t) + \mathbf{K}_d \frac{d\mathbf{e}(t)}{dt} \frac{N}{1 + N \frac{1}{s}} \quad 3-4$$

where $\mathbf{K}_p$ and $\mathbf{K}_d$ are the proportional and derivative gains respectively and N is the low pass filter coefficient [6]. A saturation is added to the output to ensure the controller can't demand more torque than the reaction wheel can provide.

3.2.Delay Implementation

Within the simulator, signal delays are accounted for by offsetting information being sent from the leader to the follower with the specified time delay from equation 3-5. The first term accounts for how long it will take for light to travel between satellites, where $|\delta \mathbf{r}|$ is the magnitude of this distance and c is the speed of light. The second term, b , is a predefined, constant 'total processing time', which accounts for any other forms of delay the signal will undergo, such as the time taken for the satellite to process the signal.

$$t_d = \frac{|\delta \mathbf{r}|}{c} + b \quad 3-5$$

3.2.1.Delay Compensation

A basic delay compensation technique is implemented assuming that the leader does not maneuver during this phase. A Smith predictor is used to predict the leader's inertial position vector, $\mathbf{p}$, and velocity vector, $\mathbf{v}$, t_d seconds in the future.

The same process is done for the rotational state, where the delayed angular velocity vector, $\boldsymbol{\omega}_d$, is assumed constant allowing the current attitude, $\boldsymbol{\theta}_{curr}$, to be calculated using the delayed attitude $\boldsymbol{\theta}_d$.

4.RESULTS OF USING DELAY COMPENSATION FOR COMMON POINTING

A test scenario is used to investigate the formation's ability to point at multiple targets across the Earth's surface. A stationary targets scenario is run with a goal separation of 350 km between the leader and follower; the separation begins at 345 km. All satellites are in 700 km altitude orbit, and a 0.2 s delay is present between the two satellites. The controller takes only the delayed inputs.

A test campaign has been carried out in order to compare the ideal error, where no delays are present, the error due to delays and the error when delay compensation is present. Figure 5 displays the true position of the follower in blue, the position of the follower in case of no delay compensation in red, and the position when the delay compensation is active in yellow. The aim of this graph is to visualise how close the behaviour of the delay-compensated position can get to the ideal position.

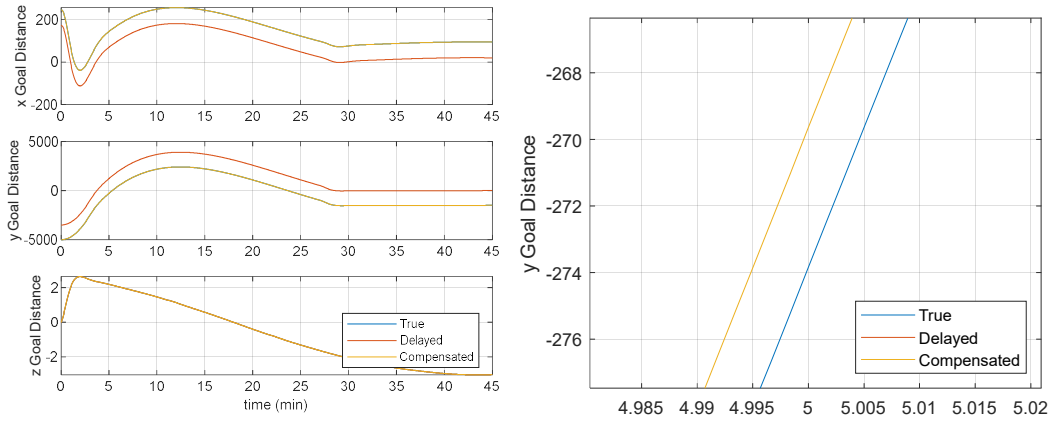


Figure 5 – Left: Follower position error with and without delay compensation. Right: $\hat{y}_{LVLH}$ axis position error at greatest relative velocity

The axis with the largest error in both the delayed and compensated position is the $\hat{y}_{LVLH}$ axis, due to it having the largest velocity component, so this axis will define the overall error. The steady state error between the true position and the delayed position is roughly 1.5 km. The performance of the delay compensation will be measured when the largest error occurs, which is when the greatest relative velocity occurs. From Figure 5 this is at roughly 5 minutes at which time the error is roughly 4 m.

Figure 6 displays the true attitude error of the follower satellite in blue, the delayed error in red and the compensated error in yellow. It should be noted the pointing accuracy is zoomed to 0.01° to allow the errors between the delayed and true pointing attitude to be viewed. The vertical bars present in Figure 6 are oscillations due to the satellites changing target. The attitude error decreases from 0.002° steady state error to less than $1e^{-5^\circ}$ in the ϕ direction while other axes show negligible errors.

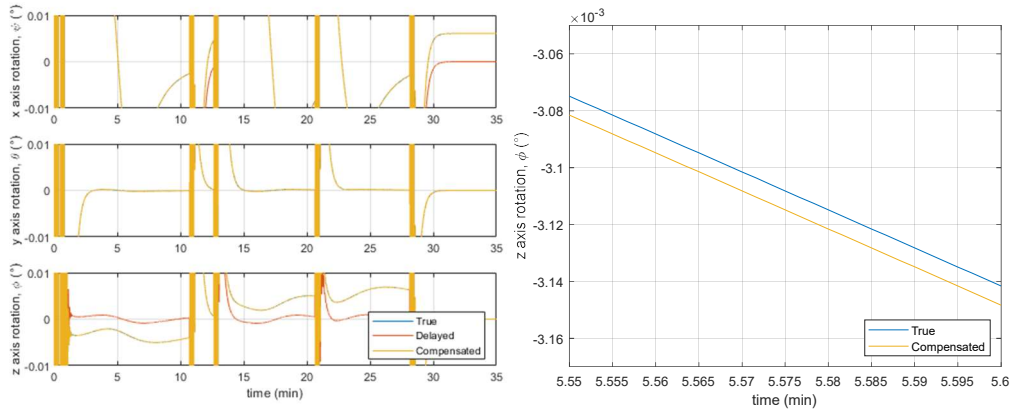


Figure 6 – Attitude Error of Follower Satellite

5.CONCLUSION

This paper describes the development of a leader-follower architecture for a swarm of satellites tasked with Earth observation. The follower satellite's target position and attitude are defined through delayed information from the leader of its position and attitude. A simple delay compensation strategy was implemented and compared with the true relative position between the two satellites.

By introducing delay compensation into the simulator, the steady-state position error of 1.5 km was reduced to 4 m due to the leader's position being inferred by numerically solving orbital equations. Similarly, the attitude error was reduced by 2 magnitudes, from 0.002° steady state error to less than $1e^{-5^\circ}$. This performance demonstrates that delays can be mitigated within the simulator, allowing for accurate mapping of a target on Earth's surface.

Future work will focus on developing the delay compensation techniques further to allow a leader with thrusters to be compensated, as under the current method, it is assumed the leader is not performing any manoeuvres. Additionally, an optimised scheduler should be introduced to maximise the number of observed targets when multiple targets are simultaneously within sight. The described architecture will also be implemented on the platforms of the FedLabs [1] project, allowing hardware-in-the-loop testing of the architecture.

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6. REFERENCES

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