5TH IAA CONFERENCE ON UNIVERSITY SATELLITE MISSIONS AND CUBESAT WORKSHOP

Iterative Learning Control Processes On-Board CubeSats

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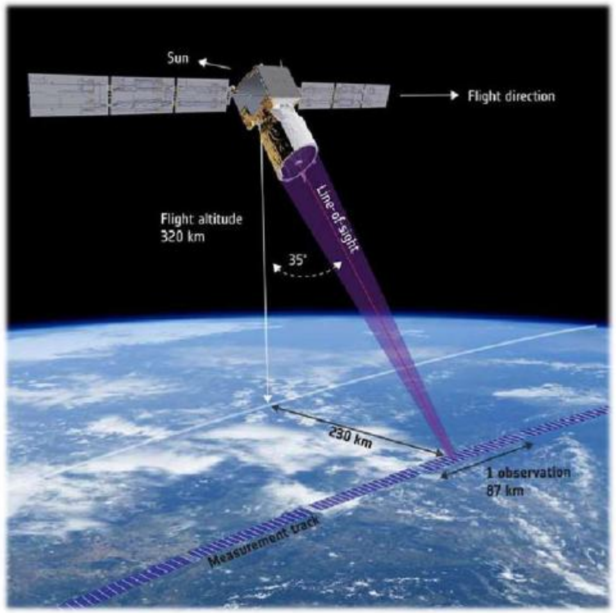
Overview

- Problem Statement
- Objective of the Research
- Satellite Numerical Model
- Iterative Learning Concept
- Proposed Approach
- Mission Definition
- Numerical Results
- Final Remarks

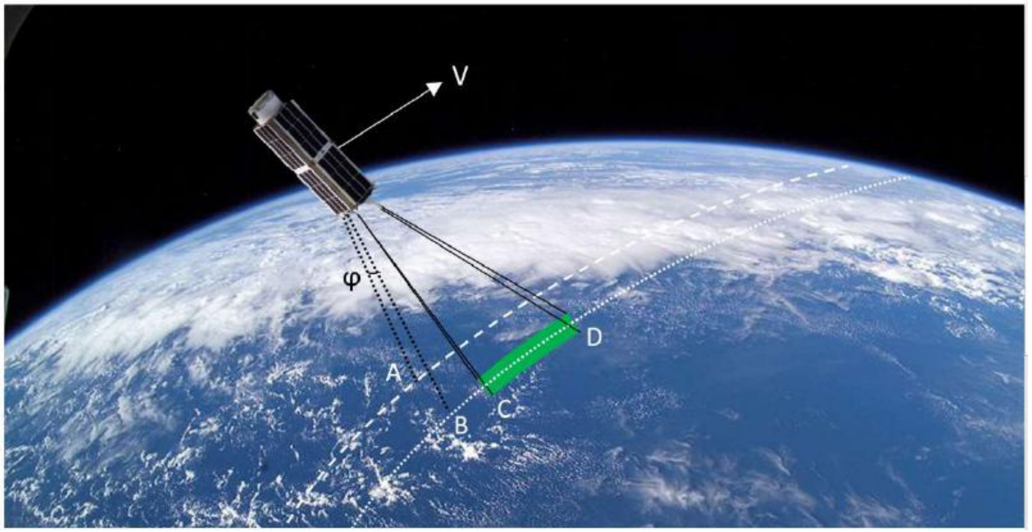
Problem Statement

Most of remote sensing and surveillance space missions are required to perform a **periodical sweep** over a prescribed terrestrial area to detect eventual changes at different times but with same viewing conditions

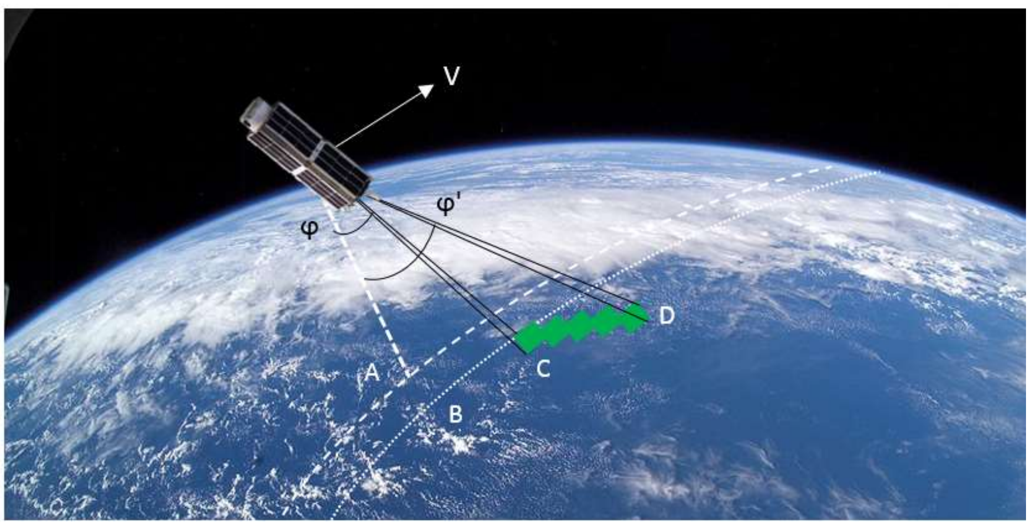


The mission can be considered as the repetition of several **identical tasks** as the spacecraft orientation should be **cyclically** modified to be identical during the data acquisition process orbit after orbit

Problem Statement (2)



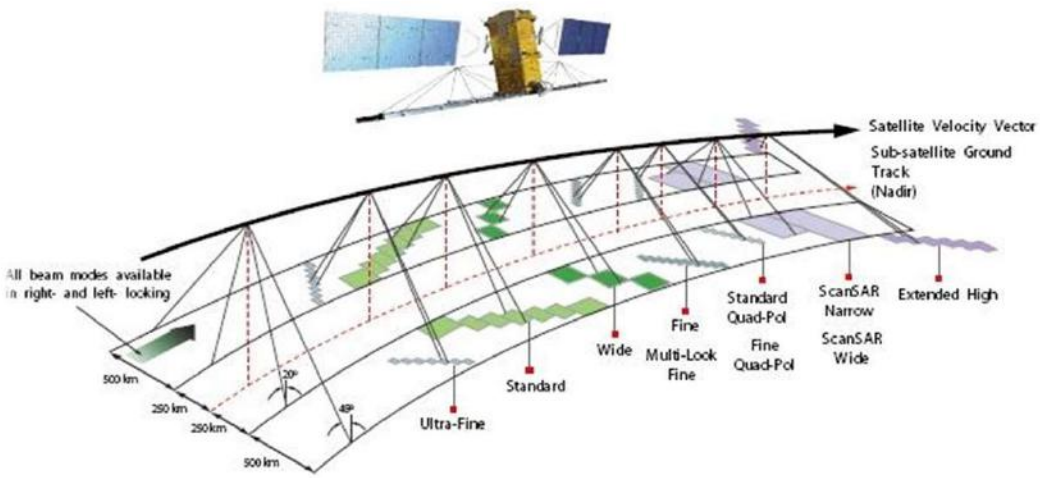
Case A: Parallel Strip



Case B: Oblique Strip

Objective of the research

Improve the attitude tracking performance of a CubeSat subjected to environmental disturbance torques repeating the same orientation manoeuvre to acquire scientific data in different orbits



APPROACH

Due to the repetitive nature of Earth observation tasks, an effective improvement in control system performance and autonomy can be obtained implementing learning-based strategies

Why?

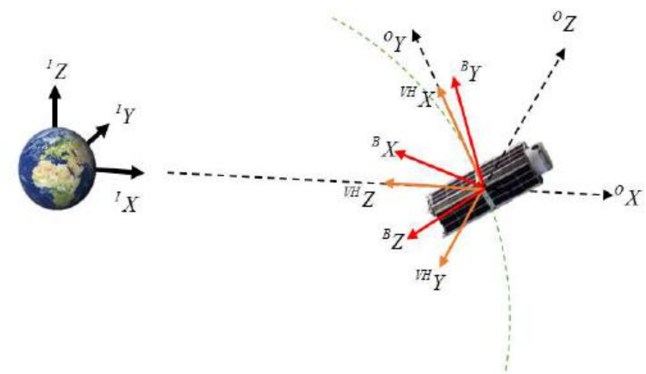
The system could **learn** from the data collected during previous iterative operations

Satellite Numerical Model

The equations of motion of a spacecraft in space environment are here derived according to a classical Lagrangian approach

The motion of a generic point P is given by

$$ {}^{I}X_{P} = {}^{I}X_{0} + \boldsymbol{R}^{\boldsymbol{T}}\left(\xi\right) $$



The matrix ***R*** describes the rotation from the inertial frame to the body-axes.

$$ \boldsymbol{R} = \underbrace{\boxed{\boldsymbol{R}_{3}}(\phi,\theta,\varphi)}_{\text{LHLV-Body}} \underbrace{\boxed{\boldsymbol{R}_{2}}(\alpha,\beta)}_{\text{Orbital-LHLV}} \underbrace{\boxed{\boldsymbol{R}_{1}}(\Omega,\mathrm{i},\varpi)}_{\text{Inertial-Orbital}} $$

By performing the relevant algebra, it is possible to obtain the non-linear dynamics of spacecraft under the gravity and gravity gradient field effects.

$$ \begin{cases} \boldsymbol{M}\ddot{X}_{P} + \boldsymbol{R}^{\boldsymbol{T}}\left[\omega \wedge \left(\omega \wedge p\right)\right] + \boldsymbol{R}^{\boldsymbol{T}}\left(\dot{\omega} \wedge p\right) = \boxed{F_{Env}} \\ p \wedge \boldsymbol{R}\ddot{X}_{P} + \boldsymbol{J}\dot{\omega} + \omega \wedge \boldsymbol{J}\omega = \boxed{C_{Env}} + \boxed{u_{C}} \end{cases} $$

Environmental generalized forces

Control Torques

$$ \begin{cases} F_{Env} = F_{G} + F_{aero} \\ C_{Env} = C_{G} + C_{aero} + C_{magn} \end{cases} $$

Gravity, Drag and Magnetic Field

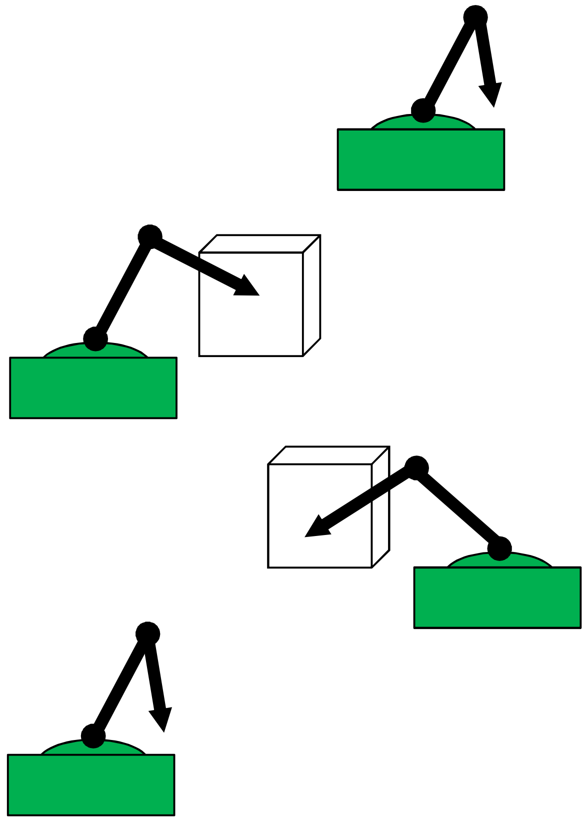
Environment Model

Gravity and Gravity Gradient	$F_G = -\boldsymbol{M}\mu_{\oplus}\frac{\hat{s}}{\lvert X_P\rvert^2}$ with $\hat{s} = \frac{X_P}{\lvert X_P\rvert}$ $\quad C_G = -\frac{\mu_{\oplus}\hat{s}}{\lvert X_P\rvert^2}(\tilde{p}\wedge\hat{s}) - \frac{3\mu_{\oplus}}{\lvert X_P\rvert^3}(\hat{s}\wedge\boldsymbol{J}\hat{s})$
Atmospheric Drag	$dF_{aero} = \begin{cases} -\frac{1}{2}C_D\rho v^2(\hat{n}\cdot\hat{v}_b)\hat{v}_b dA & (\hat{n}\cdot\hat{v}_b) > 0 \\ 0 & (\hat{n}\cdot\hat{v}_b) \le 0 \end{cases}$ $C_{aero} = \sum_{i=1}^{6} r_i \wedge F_{aero_i} = \frac{1}{2}C_D\rho v^2 \sum_{i=1}^{6} A_i(\hat{n}_i\cdot\hat{v}_b)\hat{v}_b \wedge r_i$
Magnetic Field	$B_{earth} = -\nabla V$ $V(r,\theta,\phi,t) = R_e\sum_{n=1}^{N}\sum_{m=0}^{n}(\frac{R_e}{r})^{n+1}[g_n^m(t)\cos(m\phi) + h_n^m(t)\sin(m\phi)]P_n^m(\cos\theta)$ $C_{magn} = m_{sat} \wedge B_{earth}^B$ $m_{sat} = c\,10^{-3}\, m_{sc}$

Iterative Learning Control Concept

What strategy could be used?

The Iterative Learning Control (ILC) has been conceived for those robotic systems executing the **same task repetitively**

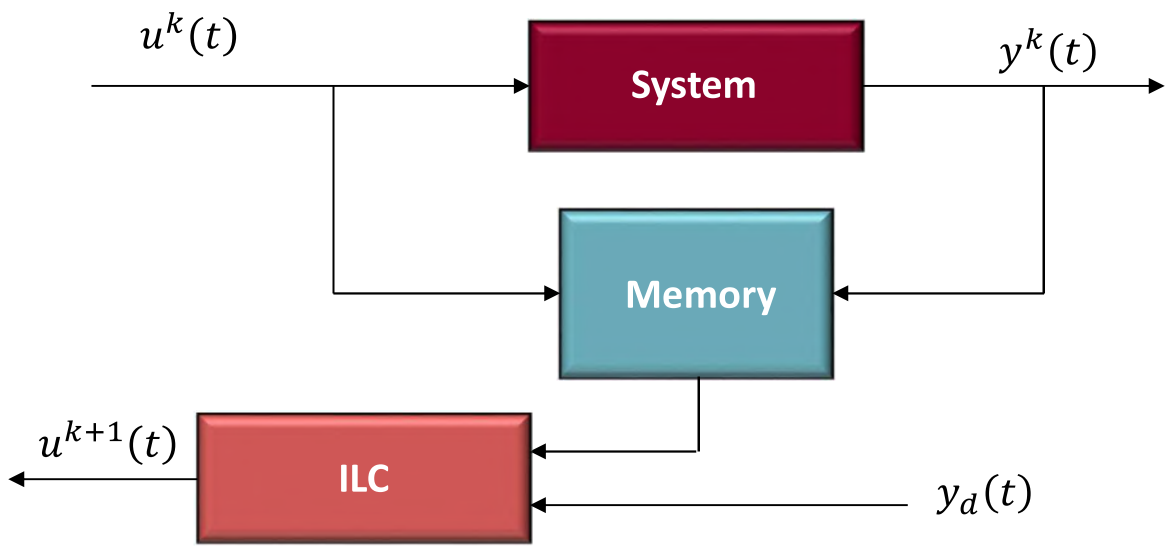


- **Step 1:** The robot at rest is waiting for workpiece
- **Step 2:** The manipulator approaches the workpiece
- **Step 3:** The part is moved to the desired position
- **Step 4:** The robot returns to rest at the initial condition

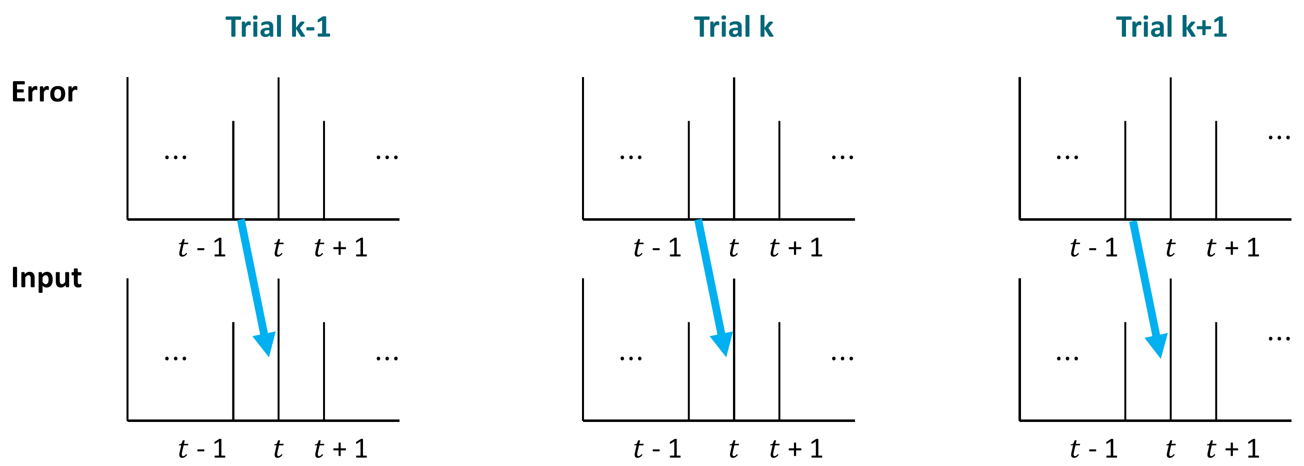
Iterative Learning Control Concept (2)

The classical Arimoto-type iterative learning scheme aims at computing a control action that leads the output to the desired value

$$u^{k+1}(t) = u^k(t) + K_{ILC}e^k(t) \quad \Longrightarrow \quad y^k(t) \to y_d(t) \quad as \quad k \to \infty$$

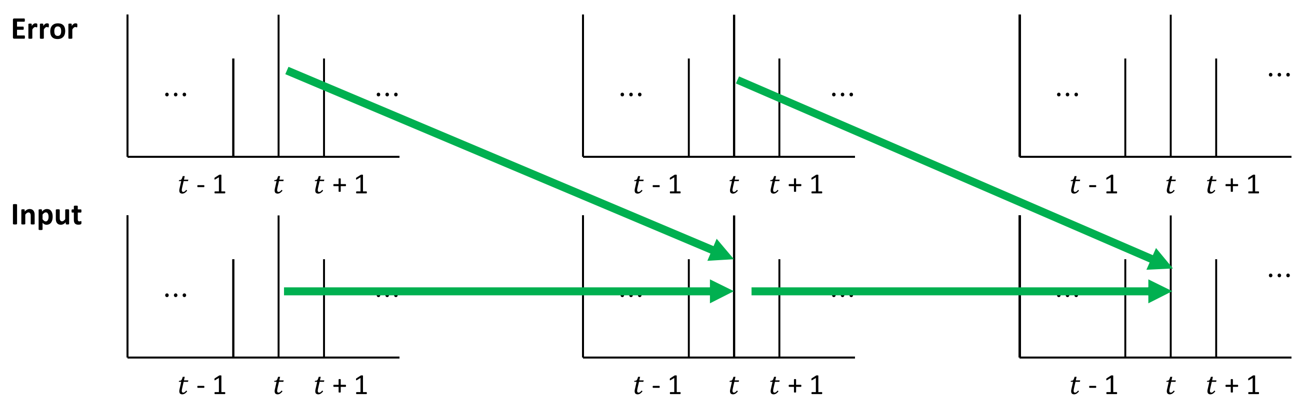


Iterative Learning Control Concept (3)



Feedback

Conventional Feedback : $u^{k+1}(t) = f(e^{k+1}(t-1))$

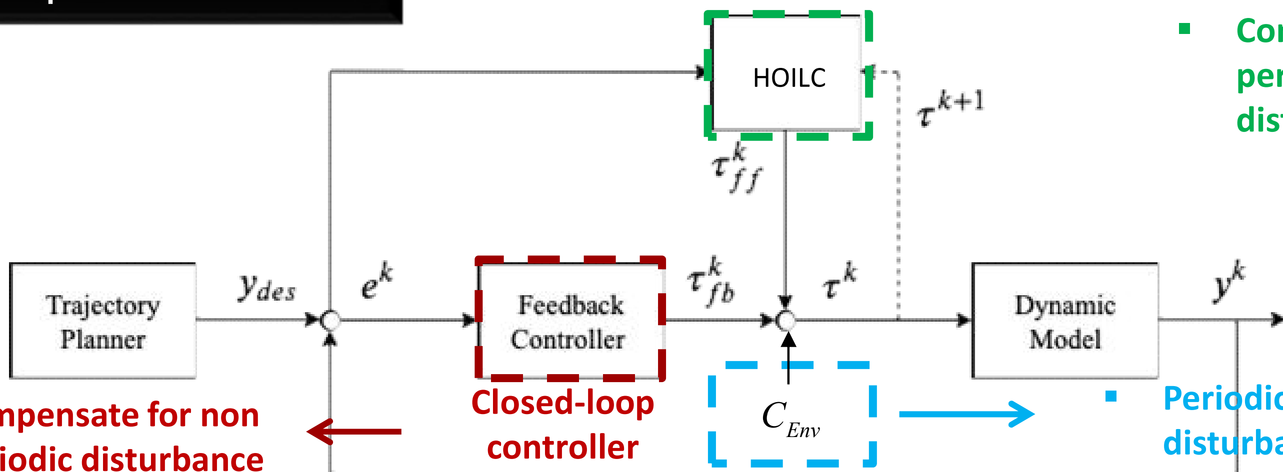


ILC

ILC: $u^{k+1}(t) = u^{k}(t) + f(e^{k}(t))$

Current Cycle Feedback (CCF) ILC

Feedback is incorporated in ILC



Iterative Learning Control

- System learns to better its actions
- Compensate for periodic disturbance

Closed-loop controller

- Compensate for non periodic disturbance
- Increase ILC learning performance

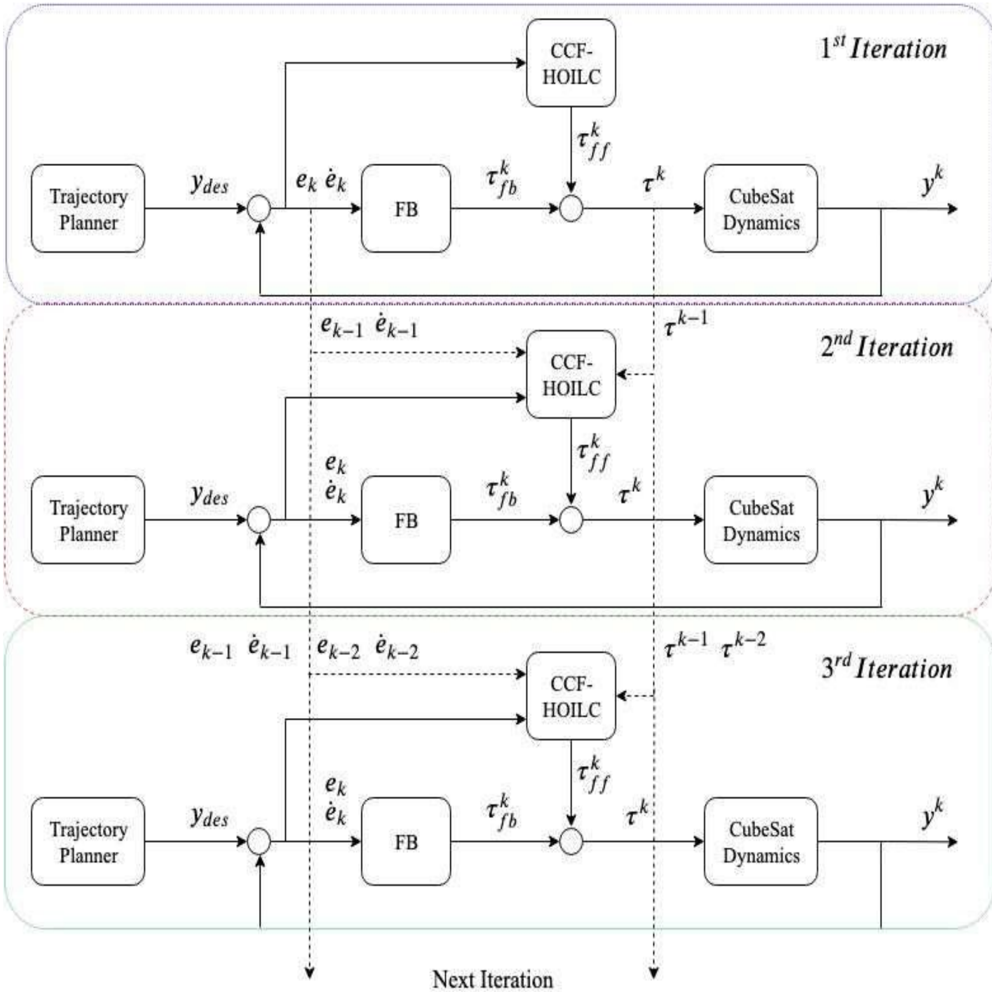
- Periodic disturbances (environmental torques)

$$\tau^k_{fb}(t) = \boldsymbol{K}_P\left(\Theta_{des} - \Theta^k(t)\right) + \boldsymbol{K}_D\left(\omega_{des}(t) - \omega^k(t)\right)$$

$$\tau^k_{ILC} = \tau^{k-1} + \boldsymbol{L}\left(\sum_{i=1}^{2} l_i\left(\Theta_{des} - \Theta^{k-i}(t)\right)\right) + \boldsymbol{D}\left(\sum_{i=1}^{2} d_i\left(\omega_{des}(t) - \omega^{k-i}(t)\right)\right) \qquad \sum_{i=1}^{2} l_i = \sum_{i=1}^{2} d_i = 1$$

HOILC: This strategy utilizes more than one past error histories generated by previous iterations control.

Proposed Control Strategy



Torque applied to the CubeSat

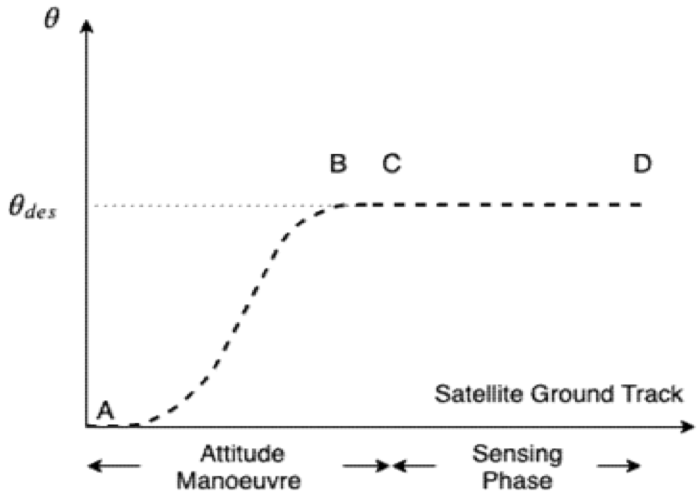
$$u_C^k(t) = -\sigma(\omega^k(t) \wedge J\omega^k(t)) + \tau_C{}^k(t)$$

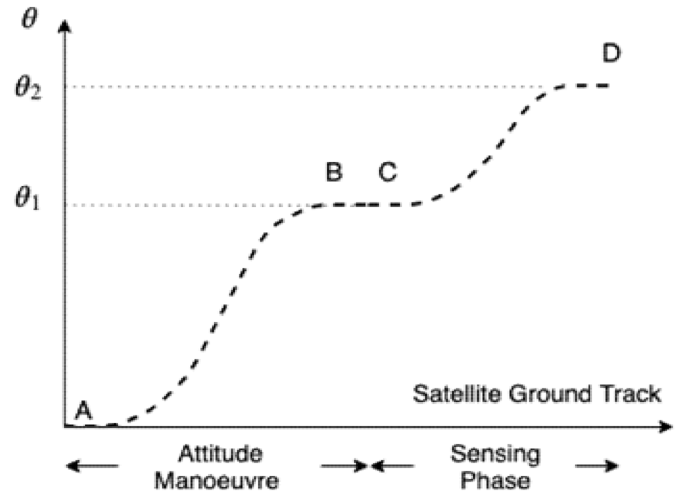
where

$$\tau_C{}^k(t) = \tau_{fb}^k(t) + \tau_{ILC}^k(t)$$

The torque is the sum of two contributions: a Feedback Term and a Feedforward Term

Mission Definition





CASE A: Tracking of the attitude manoeuvre and stabilization phase: roll-tilt of 20 degrees

CASE B: Tracking of the attitude manoeuvre and sensing phase: first roll-tilt of 20 degrees and second roll-tilt of 30 degrees

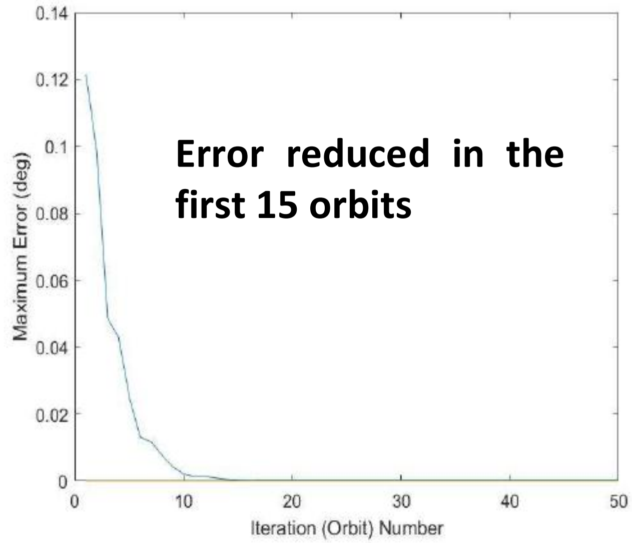
DATA: The relevant data concerning the spacecraft used in the simulation is:

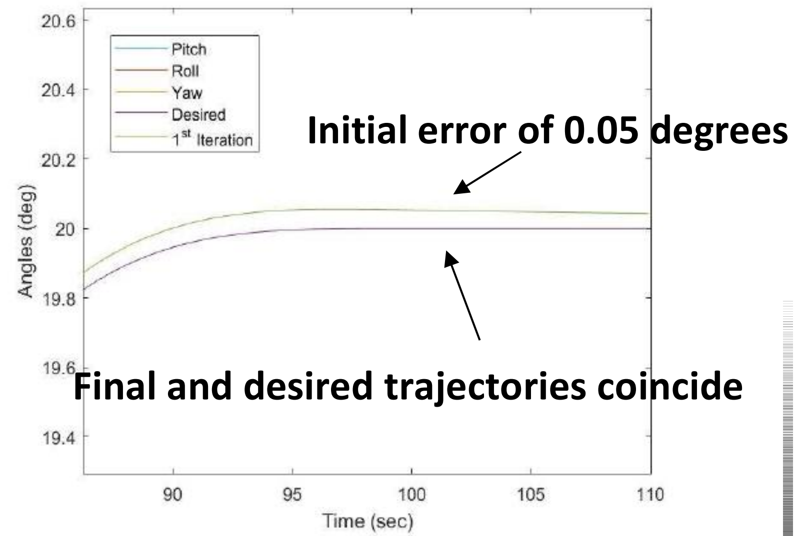
ORBIT	Symbol	Value
Eccentricity	e	0.001
Semi-major axis	a	6871 km
Inclination	i	77.6 deg
RAAN	Ω	22 deg
Argument of perigee	ω	0 deg

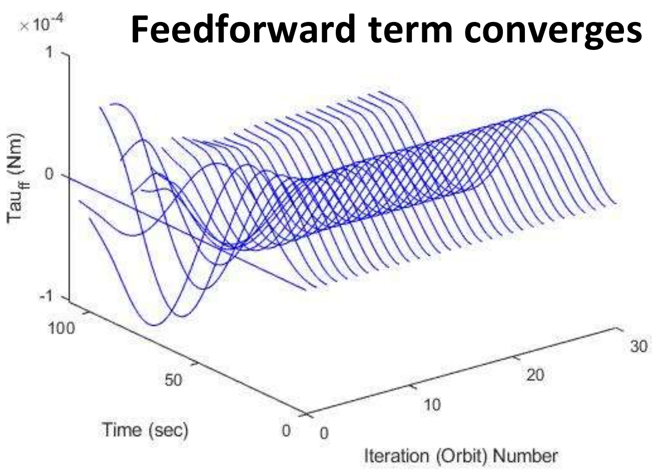
INERTIAL	Symbol	Value
Dimensions	H	0.2 m
	W	0.2 m
	D	0.2 m
Inertia	Ixx	0.166 kg m^2
	Iyy	0.166 kg m^2
	Izz	0.166 kg m^2
Mass	M	25 kg

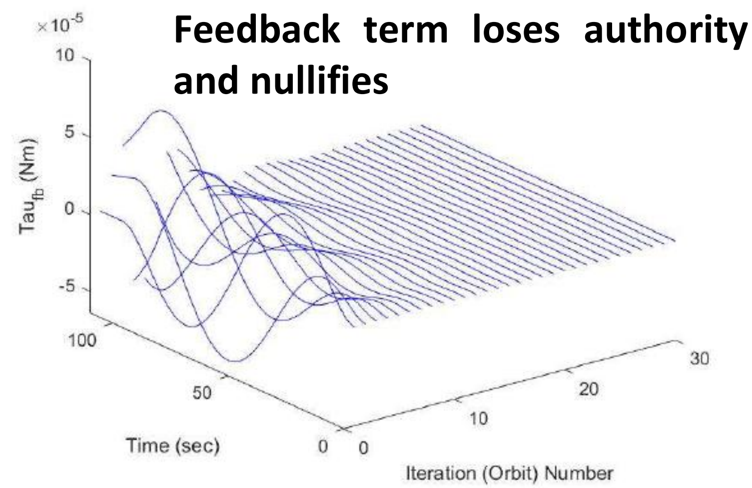
Results

CASE A



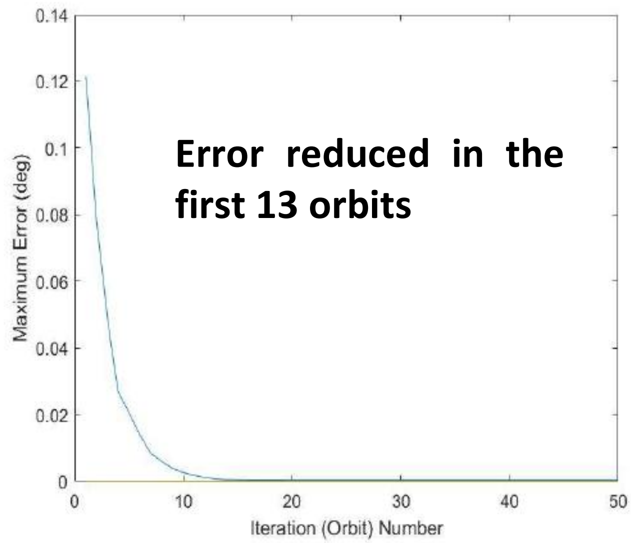




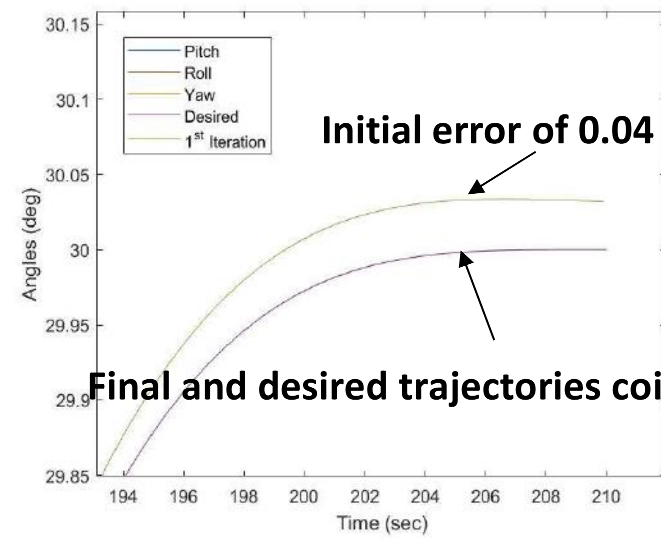


Results

CASE B



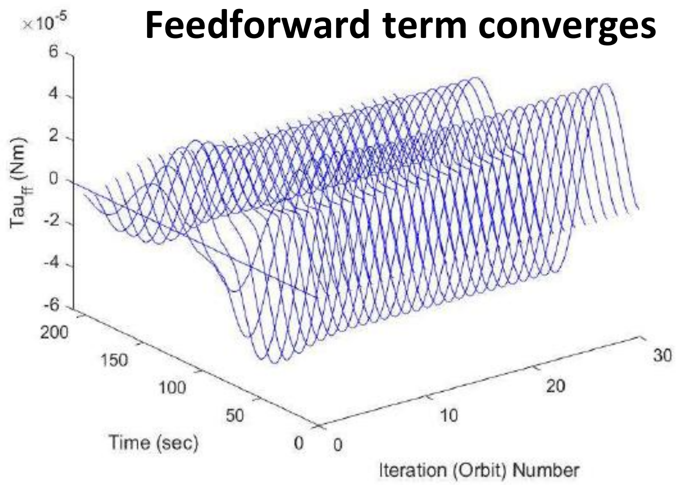
Error reduced in the first 13 orbits



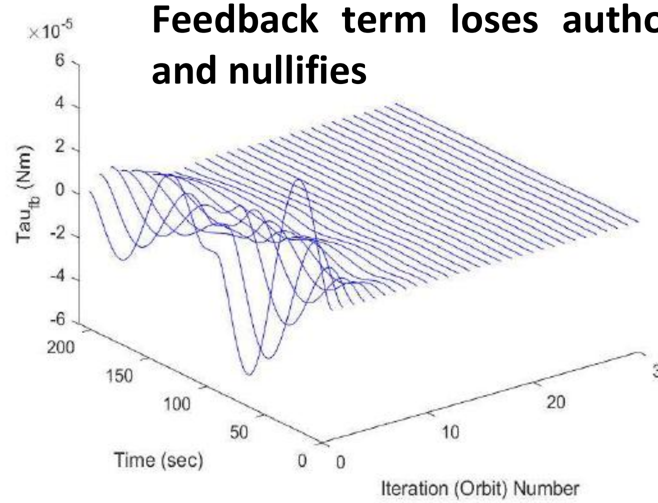
Initial error of 0.04 degrees

Final and desired trajectories coincide

Feedforward term converges



Feedback term loses authority and nullifies



Final Remarks

An investigation on an intelligent control system to improve the attitude tracking for an EO CubeSat in case of repetitive manoeuvres has been addressed in this paper

- The possibility to use on-orbit available data, which can be memorized among successive orbits, naturally calls for exploiting the gathered information to improve the system performance.
- The combination of HOILC and FB control has proved to be able to address the environmental torques as external disturbances
- The proposed controller proved to improve significantly the tracking performance of the satellite just by using available in-orbit data as attitude orientation and angular velocities. It should be noticed that **no high computational costs** are related to such control system
- As future developments, an automated and optimized selection of learning gains could be implemented to improve the autonomy of the controller

Thank you for your attention!