Università degli Studi di Napoli Federico II

Giacomo Basile

Advanced Star Tracking Control Architectures for Ground-based Telescopes: the Telescopio Nazionale Galileo Case.

Tutor: Prof. Stefania Santini **co-Tutor: Ing. Pietro Schiapani**

Cycle:XXXVII **Year:2024/2025**

information technology electrical engineering PhD

INAF Osservatorio Astronomico di Capodimonte

Background & Info

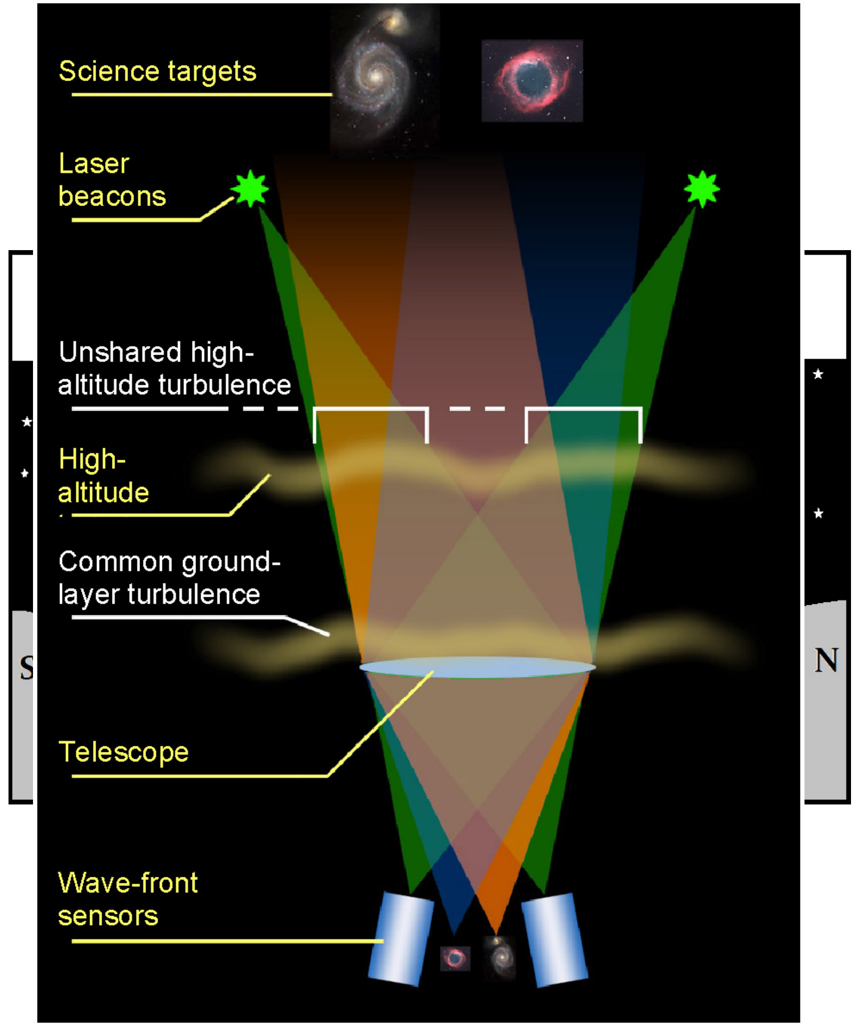
- MSc degree in Automation Engineering, University of Naples Federico II
- Research group: INAF-OACN and DAiSY Lab
- Tutor: Prof. Stefania Santini
- Co-Tutor: Ing. Pietro Schipani
- PhD start date: 01/11/2021
- Scholarship type: INAF
- Partner company: Osservatorio Astronomico di Capodimonte

Research Field of Interest

Considering a novel astronomic telescope, e.g., Very or Extremely Large Telescope (VLT, ELT), my research topics are:

I. The design and development of the adaptive optics (AO) control systems for ground-based telescopes, they aim to mitigate the atmospheric turbulence disturbance. Moreover, it is worthily noting that the AO control problem is intrinsically limited by:
   - Spatial and fitting error.
   - Temporal servo lag error.
   - Angular or Anisoplanatic error.

II. The design and development of the motion control system for ground-based telescope. Especially, the axes control system aims to pursuit the celestial body and it requires a very high tracking performance despite the presence of external disturbance such the wind force.



Summary of Study Activities

Herein the study activities over the three years PhD are summarised:

- **First Year:**
  - Study of control architectures and strategies exploited to solve the AO control problem [1].
  - Study of Reinforcement Learning (RL) and Deep RL (DRL) techniques.
- **Second Year:**
  - Study and design of tracking control architecture for ground-based telescopes [2].
  - First applications of the of DRL techniques.
- **Third Years:** Dedicated to the upgrading project of the tracking control system for the Telescopio Nazionale Galileo (TNG) [3] where I spent my period abroad.

[1] Landman, Rico, et al. *"Self-optimizing adaptive optics control with reinforcement learning for high-contrast imaging."* Journal of Astronomical Telescopes, Instruments, and Systems 7.3 (2021): 039002.

[2] Gawronski, W. K. (2008). *Modeling and control of antennas and telescopes* (p. 43). Berlin, Germany: Springer.

[3] Basile, Giacomo, et al. *"Model-based optimal tracking control architecture for ground-based telescopes."* Ground-based and Airborne Telescopes X. Vol. 13094. SPIE, 2024.

Summary of Study Activities

38 attended seminars, organized by ITEE and other international societies.

7 attended Ph.D. course, organized by ITEE and MSc .

1 attended PhD school:
“Nonlinear and data-driven model predictive control”, organized by European Embedded Control Institute (EECI)

Credit Summary:

PhD Year	Courses	Seminars	Reasearch	Tutoring/ Suplementary Teaching
1^{st}	20.0	5.0	35.80	0.2
2^{st}	14.0	9.3	37.7	0.0
3^{st}	0.0	0.0	60.0	0.0
Total	34.0	14.3	133.5	0,2
Expected	min 30 – max 70	min 10 – max 30	min 80 – max 140	min 0 – max 4.8

Research products (1/2)

[J1]	**G. Basile**, M. Gonzalez, A. Petrillo, S. Santini, S. Savarese, P. Schipani, *Model Predictive Star Tracking Control for Ground-Based Telescopes: the Telescopio Nazionale Galileo Case,* **Journal of Astronomical Telescopes, Instruments, and Systems,** SPIE. **(under review 2024)**.
[J2]	**G. Basile**, D. G. Lui, A. Petrillo, S. Santini, *Deep Deterministic Policy Gradient Virtual Coupling control for the coordination and manoeuvring of heterogeneous uncertain nonlinear High-Speed Trains,* **Engineering Applications of Artificial Intelligence,** Vol. 133, 2024, 108120.
[J3]	**G. Basile**, S. Leccese, A. Petrillo, R. Rizzo, S. Santini, *Sustainable DDPG-based Path Tracking For Connected Autonomous Electric Vehicles in extra-urban scenarios,* **IEEE Transactions on Industry Applications,** pp. 1-13, 2024.
[J4]	**G. Basile**, E. Napoletano, A. Petrillo, S. Santini, *Roadmap and challenges for reinforcement learning control in railway virtual coupling,* **Discover Artificial Intelligence,** 2(1), 27, 2022,
[J5]	S. Savarese, P. Schipani, G. Capasso, M. Colapietro, S. D'Orsi, S., M. Iuzzolino, **G. Basile**, *Software solutions for numerical modeling of wide-field telescopes.* ***arXiv preprint arXiv:2112.06857.***

[C1]	**G. Basile**, D.G. Lui, E., Napoletano, A. Petrillo, S. Santini, LSTM-based predictive control for cooperative driving of connected vehicles, Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles (ESARS) and International Transportation Electrification Conference (ITEC), August 2024, IEEE. **(accepted).**
[C2]	**G. Basile**, M. Gonzalez, A. Petrillo, S. Santini, S. Savarese, P. Schipani, *Model-based optimal tracking control architecture for ground-based telescopes,* **In Ground-based and Airborne Telescopes X,** Yokohama, Japan, August 2024, Vol. 13094, pp. 1432-1443, SPIE.

Thesis Product.

Research products (2/2)

[C3]	**G. Basile**, D: G. Lui, A. Petrillo, S. Santini, *Adaptive Distributed PI-like Control Protocol for the Virtual Coupling of Connected Heterogeneous Uncertain Nonlinear High-Speed Trains,* **31st Mediterranean Conference on Control and Automation (MED),** Limassol, Cyprus, June 2023, pp. 674-679, IEEE.
[C4]	**G. Basile**, S. Leccese, A. Petrillo, R. Rizzo, S. Santini, *Sustainable DDPG-based Path Tracking For Connected Autonomous Electric Vehicles in extra-urban scenarios,* **In *2023 IEEE IAS Global Conference on Renewable Energy and Hydrogen Technologies, GlobConHT 2023*,** Maldives, March 2023, pp. 1-7. IEEE.
[C5]	**G. Basile**, D. G. Lui, A. Petrillo, S. Santini, *Deep deterministic policy gradient-based virtual coupling control for high-speed train convoys,* **In 2022 IEEE International Conference on Networking, Sensing and Control (ICNSC),** Shanghai, China, December 2022, pp. 1-6, IEEE.
[C6]	**G. Basile**, A. Petrillo, S. Santini, *Ddpg based end-to-end driving enhanced with safe anomaly detection functionality for autonomous vehicles,* **In 2022 IEEE International Conference on Metrology for Extended Reality, Artificial Intelligence and Neural Engineering (MetroXRAINE),** Rome, Italy, October 2022, pp. 248-253, IEEE.
[C7]	S. Savarese, P. Schipani, G. Fiorentino, L. Schreiber, **G. Basile**, G. Capasso, M. Colapietro, S. D'Orsi, L. Marty, F. Perrotta, *Modeling wide-field telescopes in presence of misalignments: an application to the Vera C. Rubin Observatory,* **In Modeling, Systems Engineering, and Project Management for Astronomy X,** Montréal, Canada, 2022, Vol. 12187, pp. 594-602, SPIE.
[C8]	**G. Basile**, D. G. Lui, A. Petrillo, S. Santini, *Acc fuzzy-based control architecture for multi-body high-speed trains with active inter-cars couplers,* **In European Dependable Computing Conference,** Zaragozza, Spain, September 2022, pp. 126-138, Cham: Springer International Publishing.

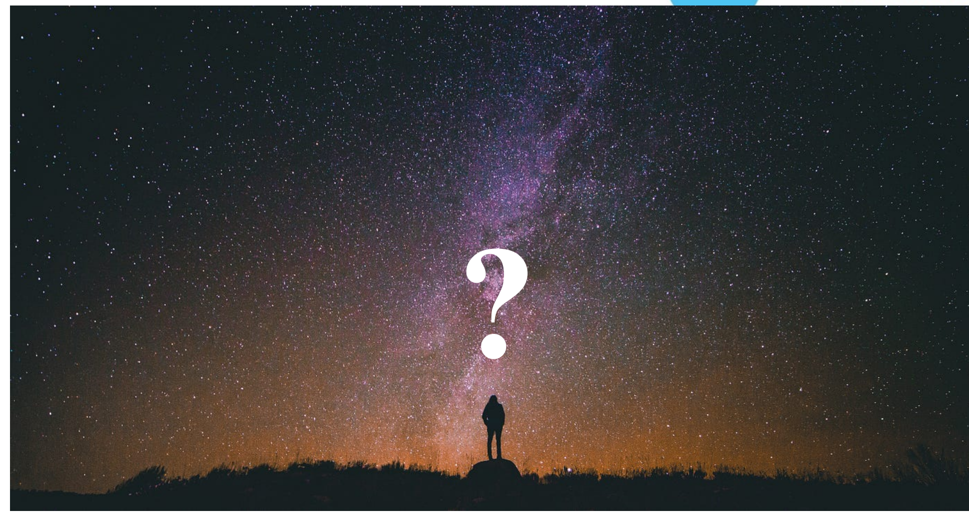
Thesis Product.

The Ground-based Telescope

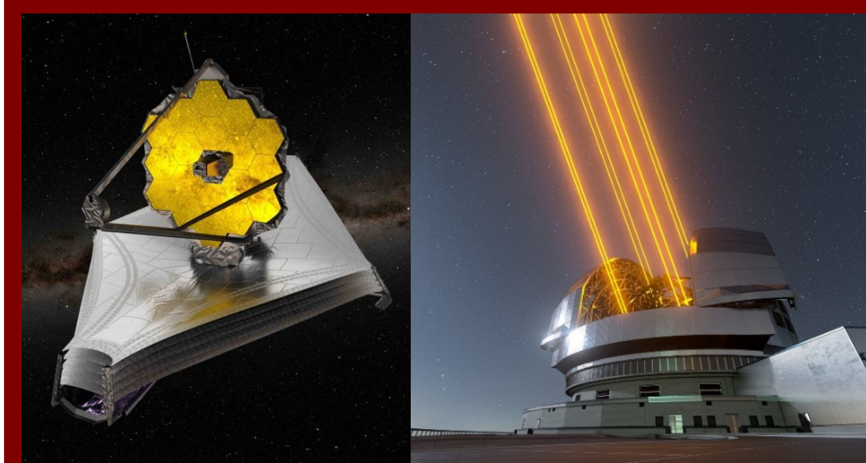
Where did we come from?

How did the universe begin?

Are we alone?



The invention of ground-based telescopes and space telescopes. For instance, James Webb and E-ELT



Promising Solution: the ground-based telescope.

- Thanks to the AO systems, they can provide high-resolution data.
- They are easy to install and maintain.

The Challenge !

Improve the tracking performance of the ground–based telescope!

Tracking Control Problem For Ground-Based Telescope: Problem Statement (1/3)

Tracking Control Problem:

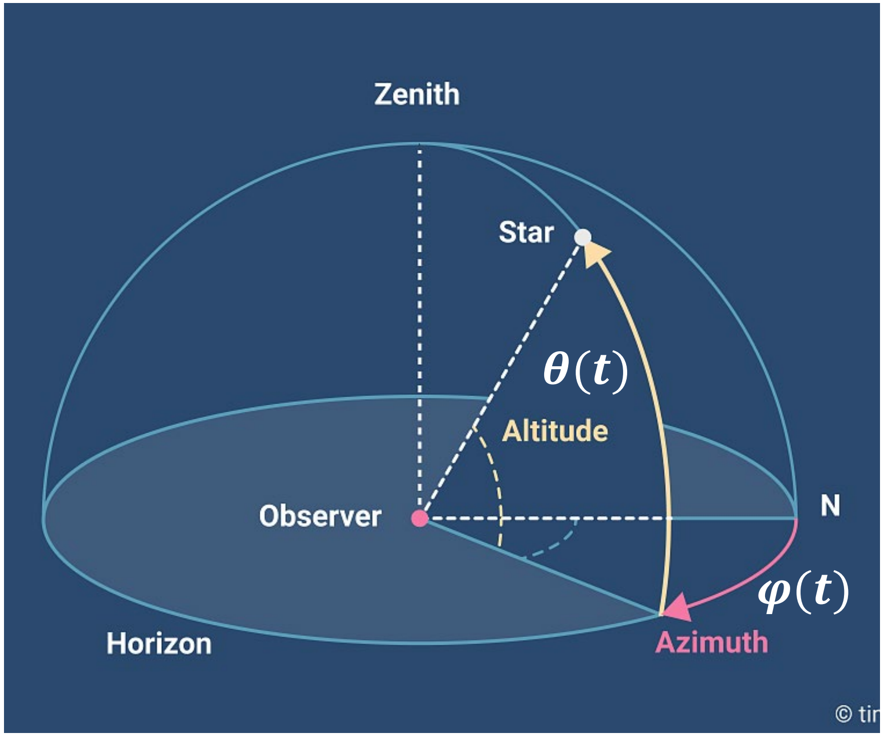
- Let's considering a novel astronomic telescope, e.g., Very or Extremely Large Telescope (VLT, ELT), regarding axes control problem is decoupled by considering the azimuth coordination system, i.e.:

  i) the elevation axis $\theta(t)$

  ii) the azimuth axis $\varphi(t)$.

- Moreover, the telescope motion controller have to cope with:

  - Unmodelled dynamics
  - External disturbance such as the wind force
  - Mitigate the measurement noise.



Tracking Control Problem For Ground-Based Telescope: Problem Statement (2/3)

Consider a ground-based telescope in the azimuth coordination system, labeled with $\vartheta(t)$ for the altitude and $\varphi(t)$ for the azimuth, and described by the following LTI system:

$$\dot{x}(t) = Ax(t) + B\big(u(t) - \delta(t)\big)$$
$$y(t) = Cx(t) + \omega, \qquad (1)$$

with

$$A = \begin{bmatrix} A_e & 0_{6\times6} \\ 0_{6\times6} & A_a \end{bmatrix}, B = \begin{bmatrix} B_e & 0_{6\times1} \\ 0_{6\times1} & B_a \end{bmatrix}, C = \begin{bmatrix} C_e & 0_{1\times6} \\ 0_{1\times6} & C_a \end{bmatrix},$$

Being:

- $\boldsymbol{x}(\boldsymbol{t}) \in \mathbb{R}^{12}$ the flexible dynamics of the telescope;
- $\boldsymbol{u}(\boldsymbol{t}) = [\boldsymbol{\tau_e}(\boldsymbol{t}) \quad \boldsymbol{\tau_a}(\boldsymbol{t})] \in \mathbb{R}^2$ the altitude and azimuth torques;
- $\boldsymbol{y}(\boldsymbol{t}) = [\dot{\boldsymbol{\vartheta}}(\boldsymbol{t}) \quad \dot{\boldsymbol{\varphi}}(\boldsymbol{t})] \in \mathbb{R}^2$ the altitude and azimuth speed measurements,
- $\boldsymbol{\delta}(\boldsymbol{t}) \in \mathbb{R}^2$ the input wind disturbance described via the Von-Karman Wind PSD **[4]** in (2) as:

$$\delta(t) = \sum_{j=1}^{D} \sqrt{2\,\alpha\, S_\tau(f_j)\,\Delta f}\,\cos(2\,\pi\, f_j\, t + \phi) \qquad (2)$$

- $\boldsymbol{\omega}$ is the measurements white noise affecting the output vector $y(t)$.

The matrices describing the telescopes dynamics are such that the following assumption hold.

Assumption 1. The pair (A,B) is stabilizable.
Assumption 2. The pair (A,C) is observable.
Assumption 3. C is a full row rank matrix.

[4] Marchiori, Gianpietro, et al. "ELT Telescope: control system dynamic simulations.“. *Modeling, Systems Engineering, and Project Management for Astronomy VIII*. Vol. 10705. SPIE, 2018.

Tracking Control Problem For Ground-Based Telescope: Problem Statement (3/3)

The Tracking Control Problem:

Consider the ground-based telescope dynamics as in (1). Let the scientific target star be expressed, within the azimuth coordination system, hence, in terms of the vector $y^\star(t) = [\vartheta^\star(t),\ \varphi^\star(t)]^\top$, being $\vartheta^\star(t)$ the altitude and $\varphi^\star(t)$ the azimuth reference trajectories respectively. Design an optimal-based control tracking architecture such that the telescope torques $u(t) = [\tau_e,\ \tau_a]^\top$ can properly drive the altitude and azimuth telescope axes toward the star scientific target by avoiding violating the admissible physical constraints and fulfilling the following control objective:

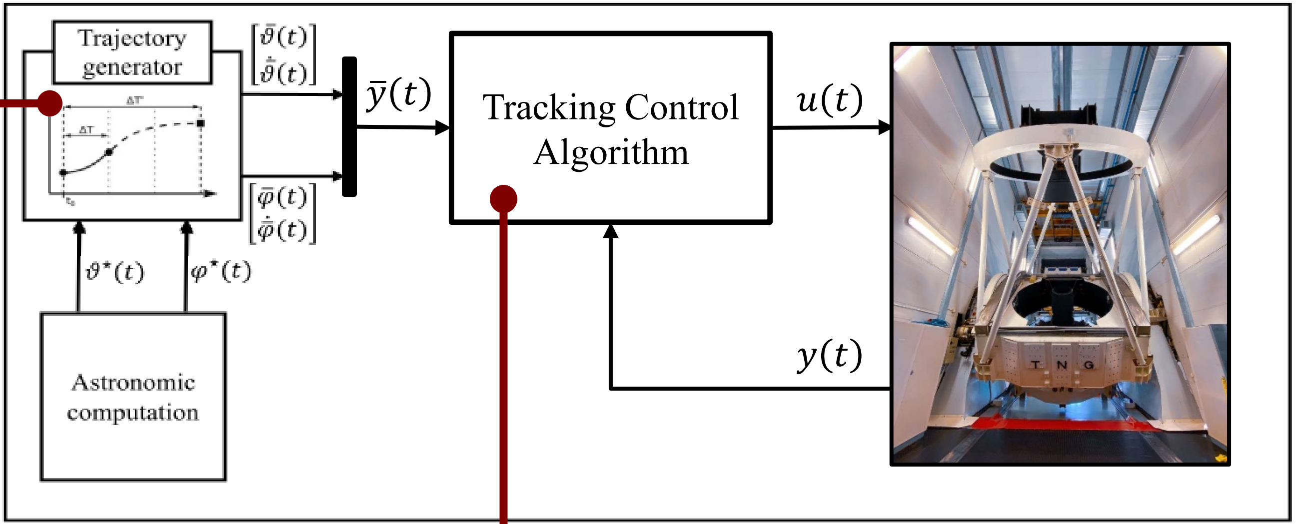
$$\lim_{t\to+\infty} \left\| y^\star(t) - \int_0^t y(\rho)\, d\rho \right\|_2 = 0 \qquad (3a)$$

$$\lim_{t\to+\infty} \|\dot{y}^\star(t) - y(t)\||_2 = 0, \qquad (3b)$$

despite the presence of the input wind disturbance $\delta(t)$ and noise measurements ω.

Ground-based telescope Tracking Control Architectures Design (1/4)

The two proposed tracking control solutions in [5], [6] can be summarized as in Figure:



Trajectory generator: embedded on both control architecture, the TG computes the safe and physical admissible reference position and velocity telescope trajectories.

Proposed Tracking control algorithm:

- **The first solution:** the Optimal Tracking Control Architecture (OTCA) [5] a double loop control scheme
  - Speed layer → Optimal Output Feedback Control.
  - Position layer → LQG-PI approach.
- **The second solution:** the MPC-based Tracking Control Architecture [6].

[5] Basile, G., et al. *"Model-based optimal tracking control architecture for ground-based telescopes"*, in Ground-based and Airborne Telescopes, August 2024, Vol. 13094, pp. 1432-1443, SPIE.

[6] Basile, G. et al. *" Model Predictive Star Tracking Control for Ground-Based Telescopes: the Telescopio Nazionale Galileo Case"*, JATIS Journal, SPIE

Ground-based telescope Tracking Control Architectures Design (2/4)

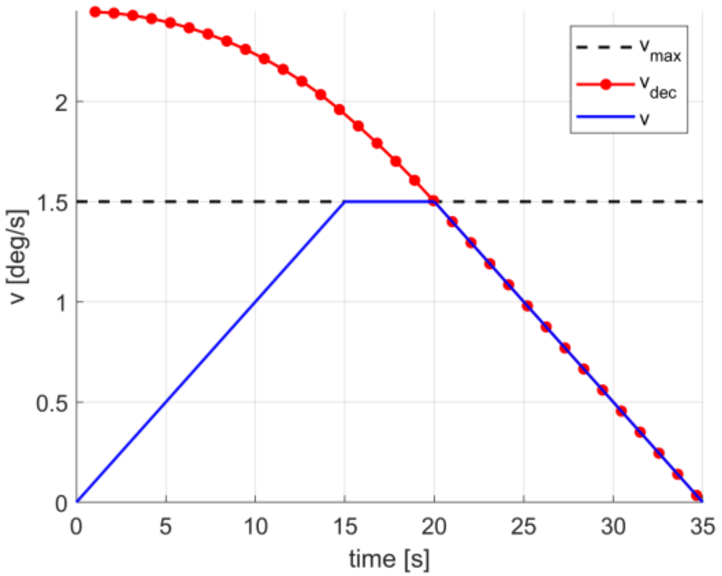
Trajectory-Generator:

According to **[7]** the TG is designed by leveraging the trapezoidal speed profile approach, i.e.:

$$\begin{aligned} \dot{y}_p(t) &= \bar{v} \\ \dot{\bar{v}} &= saturation(v_a(t), \min(v_d(t) - v_{max})) \end{aligned} \qquad (4)$$

$s.t.$

$$\begin{aligned} v_a(t) &= v(t - \Delta t) + a_{max}\,\Delta t \\ v_d\,(t) &= \dot{y}^\star(t) + sign\big(\varepsilon(t)\big)\sqrt{2\,a_{max}|\varepsilon|} \\ \varepsilon(t) &= y^\star(t) - y(t), \end{aligned} \qquad (5)$$



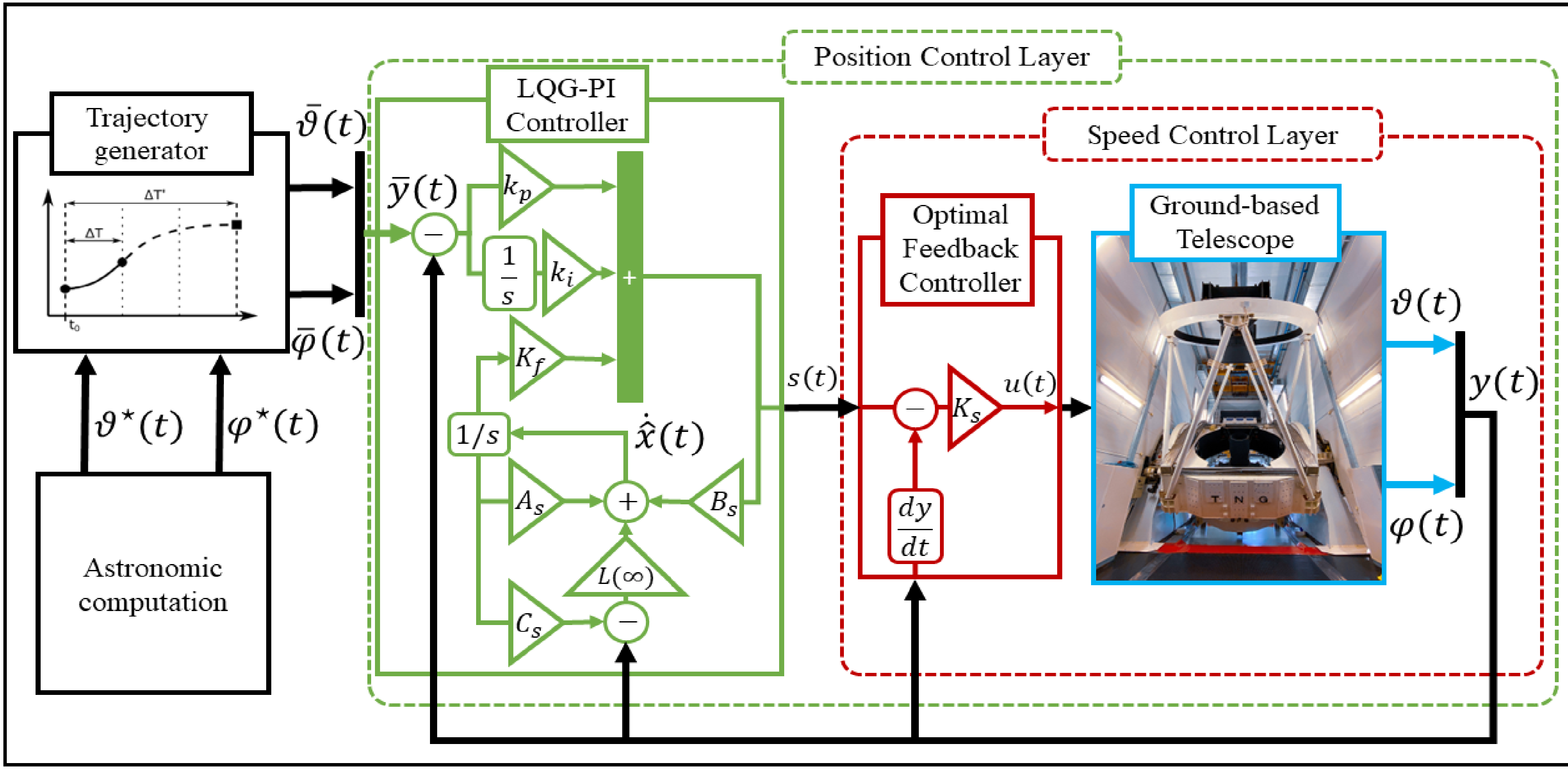
Begin:

- $v_a(t)$ is the speed during the acceleration phase.
- $v_d(t)$ is the speed during the deceleration phase.
- Δt is the sample time.
- a_{max} is the telescope admissible acceleration.
- $\varepsilon(t)$ is the tracking error.
- $y^\star(t)$ and $\dot{y}^\star(t)$ are the position and speed references.

[7] S. Savarese, et al. *"Trajectory generation methods for radio and optical telescopes"*, in Ground-based and Airborne Telescopes VIII, 11445, pp. 959–970, SPIE, 2020

Ground-based telescope Tracking Control Architectures Design (3/4)

Optimal Tracking Control Architecture:



Ground-based telescope Tracking Control Architectures Design (3/4)

Optimal Tracking Control Architecture:

Speed Control Layer:

Assumption 4. The reference speed profile s(t) is provided by the following reference generator system $\dot{s}(t) = F\, s(t)$.

According to **[8]**, the control input is:

$$u(t) = K_s\, y(t) + K_r\, s(t) \tag{6}$$

Let Assumptions 1,3 and 4 hold.
Find the optimal control gains K_s and K_r such that:

- Minimise the performance cost function

$$\|z(t)\|_2 = \big(s(t) - y(t)\big)^{\top} Q_s (s(t) - y(t)) + u(t)^{\top} R_s u(t), \tag{7}$$

- Ensuring the disturbance attenuation L_2 -gain condition:

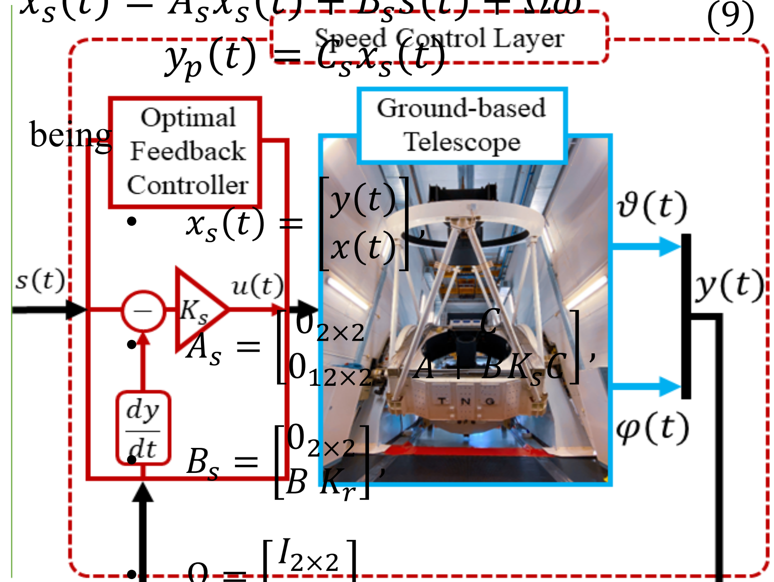
$$\frac{\int_0^{\infty} e^{-\upsilon(\rho - t)} \|z\|_2 d\rho}{\int_0^{\infty} e^{-\upsilon(\rho - t)} \|\delta(t)\|_2 d\rho} < \eta^2 \tag{8}$$

Closed-loop speed layer dynamics

$$\dot{x}_s(t) = A_s x_s(t) + B_s s(t) + \Omega\omega$$
$$y_p(t) = C_s x_s(t) \tag{9}$$

being

- $x_s(t) = \begin{bmatrix} y(t) \\ x(t) \end{bmatrix}$,
- $A_s = \begin{bmatrix} 0_{2\times2} & C \\ 0_{12\times2} & A + BK_sC \end{bmatrix}$,
- $B_s = \begin{bmatrix} 0_{2\times2} \\ B\, K_r \end{bmatrix}$,
- $\Omega = \begin{bmatrix} I_{2\times2} \\ B\, K_s \end{bmatrix}$,
- $C_s = \begin{bmatrix} I_{2\times2} \\ 0_{2\times12} \end{bmatrix}^{\top}$.



[8] Moghamad, R. & Lewis, F. L. (2019), "*Output-feedback H_∞ quadratic tracking control of linear system using reinforcement learning*". International Journal of Adaptive Control and Signal Processing, 33(2), 300-314.

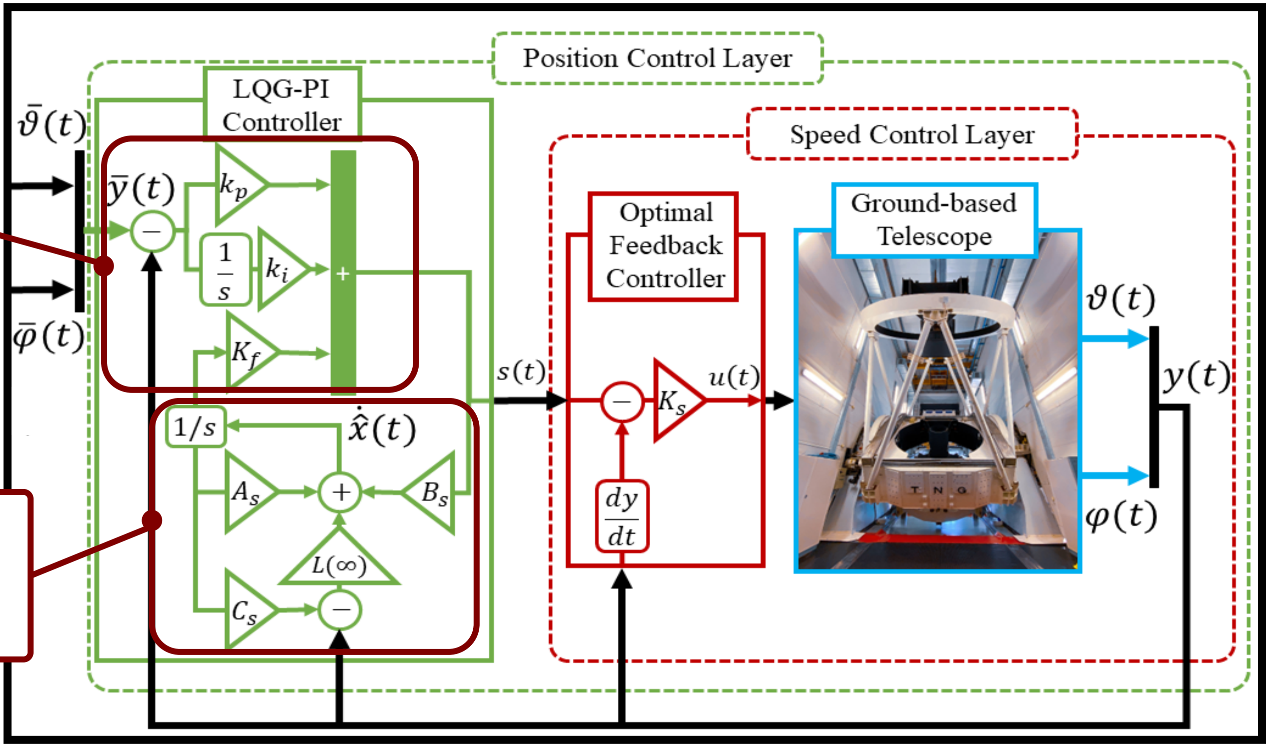
Ground-based telescope Tracking Control Architectures Design (3/4)

Optimal Tracking Control Architecture:

Position Control Layer:

Linear Quadratic Regulator with Proportional Integral actions.

Infinite Kalman Filter State Observer



Ground-based telescope Tracking Control Architectures Design (3/4)

Optimal Tracking Control Architecture:

Position Control Layer:

Kalman Filter Observer

Designed to properly estimate the model in (8), its dynamics are formalized as:

$$\dot{\hat{x}}_s(t) = A_s \hat{x}_s(t) + B_s s(t) + L_\infty \left(\bar{y}_p(t) - \hat{y}_p(t) \right) \quad (10)$$
$$\hat{y}_p(t) = C_s \hat{x}_s(t)$$

Let the following assumption hold

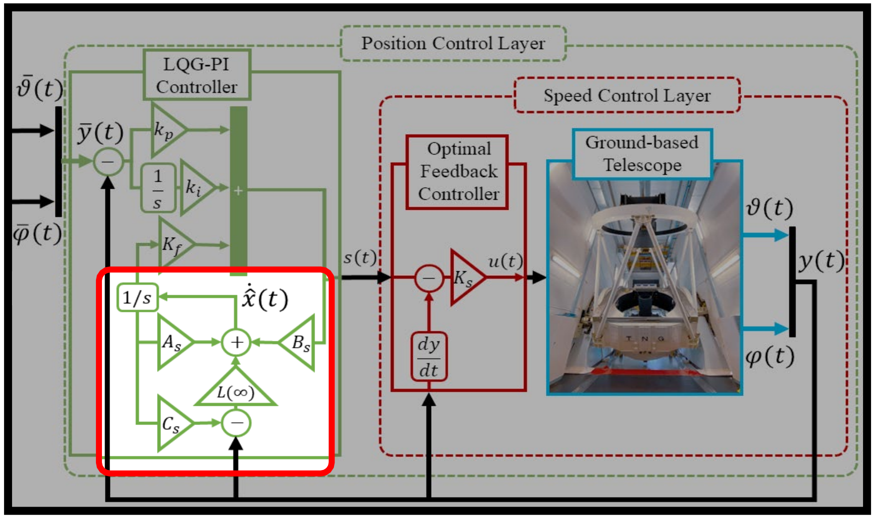
Assumption 5. The couple (A_s, B_s) and (A_s, C_s) is reachable and observable, respectively.

Then, the Kalman gain is computed as:

$$L_\infty = \bar{P}_\infty C_s^\top R^{-1} \quad (11)$$

being $\bar{P}$ the unique solution of the Riccati equation:

$$0 = A_s \bar{P}_\infty + \bar{P}_\infty A_s^\top + \bar{Q} - \bar{P}_\infty C_s^\top \bar{R} C_s \bar{P}_\infty \quad (12)$$



Ground-based telescope Tracking Control Architectures Design (3/4)

Optimal Tracking Control Architecture:

Position Control Layer:

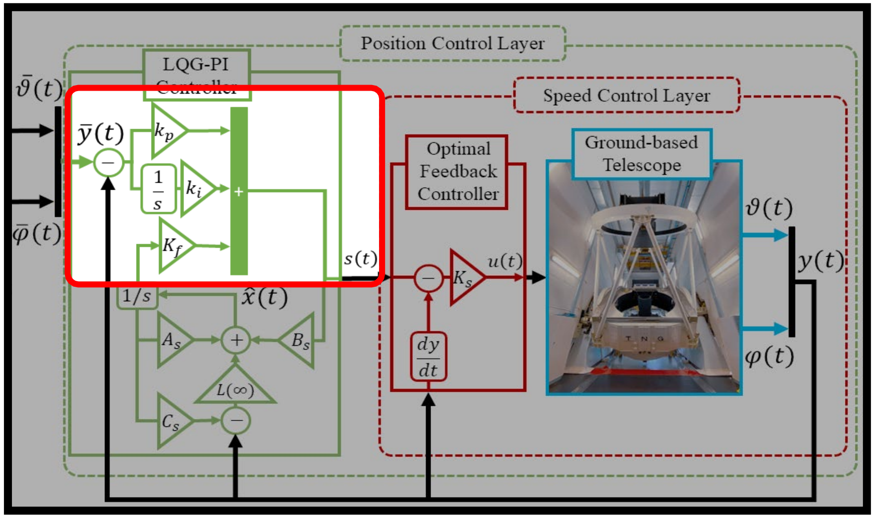
Linear Quadratic Regulator Proportional-Integrative

Considering the following system to be controlled

$$\dot{x}_T(t) = A_T x_T(t) + B_T s(t) \qquad (13)$$

being $x_T = [e_i(t) \quad e_p(t) \quad \hat{x}_s(t)]^\top, e_p(t)$ the tracking errors and its $e_i(t)$ integrative.
Then, under the action:

$$s(t) = K_c x_T(t) \qquad (14)$$
$$being$$
$$K_c = [k_i \quad k_p \quad K_f]^\top.$$



Let the following assumption hold

Assumption 6. The pair (A_T, B_T) is completely reachable and controllable.

Hence, K_c is tuned by minimizing the following cost function:

$$J_c(t) = \int_0^\infty x_T(t)\, Q_c\, x_T^\top(t) + s(t)\, R_c\, s^\top(t)\, dt \qquad (15)$$

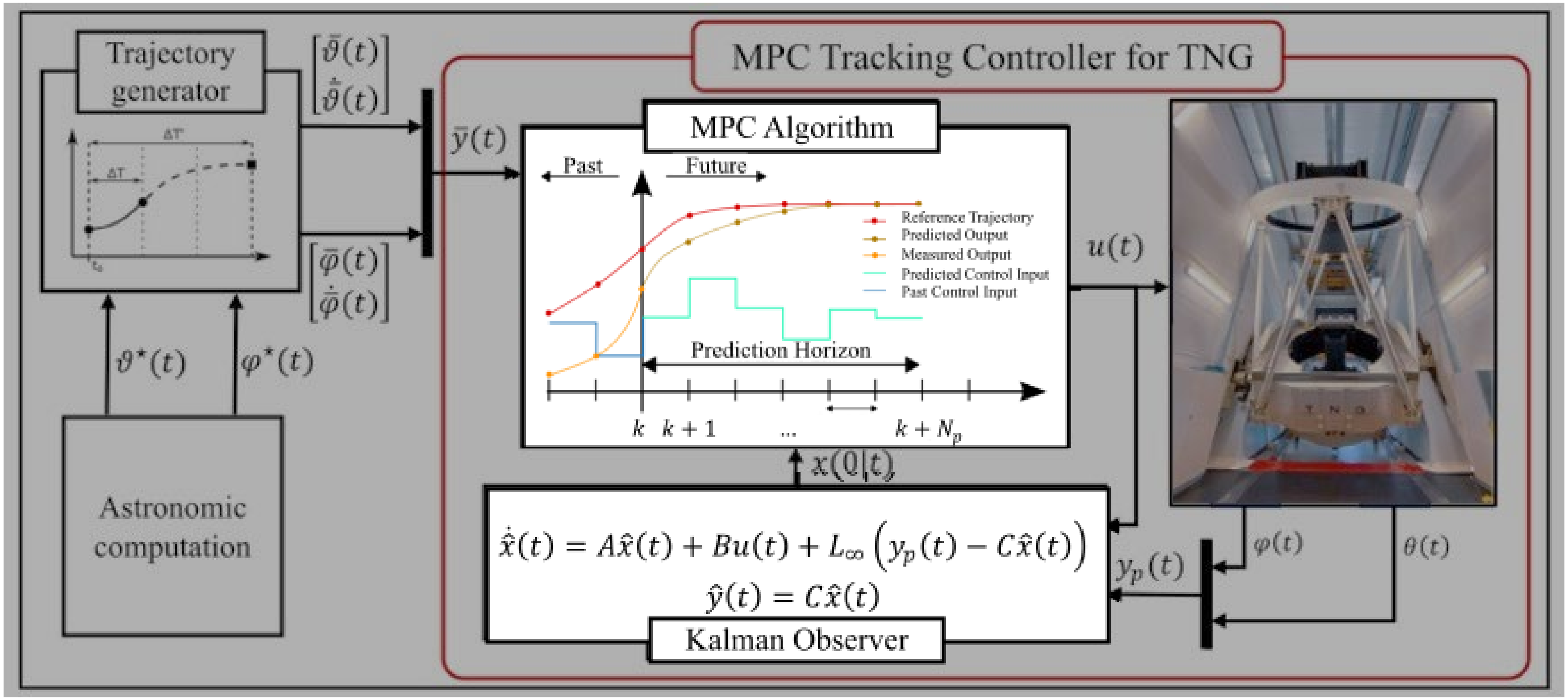
where $Q_c \geq 0 \in \mathbb{R}^{18\times18}$ and $R_c > 0 \in \mathbb{R}^{2\times2}$ are diagonal weighting matrices.

Stability Remark

The final step of our design consists in defining the matrix F in Ass. 4. Given the position control $s(t)$ in (14) and the augmented state $x_T(t)$ in (13) it follows that the matrix F is such that $F = K_c(A_T + B_T K_c)$. (16)

Ground-based telescope Tracking Control Architecture Desing (4/4)

MPC-based Tracking Control Architecture:



Ground-based telescope Tracking Control Architecture Desing (4/4)

MPC-based Tracking Control Architecture:

With the aim of predicting and control the position and velocity dynamics of the telescope so fulfil the control objective in (3a) and (3b), we consider the following dynamical system

$$\begin{aligned} \dot{x}_m(t) &= A_m x_m(t) + B_m\big(u(y) - \delta(t)\big) \\ y_m(t) &= C_m x_m(t), \end{aligned} \tag{16}$$

being $x_m(t) = [y(t) \quad x(t)]^\top$ and:

$$A_m = \begin{bmatrix} 0_{14\times 2} & \begin{vmatrix} C \\ A \end{vmatrix} \end{bmatrix}, \qquad B_s = \begin{bmatrix} 0_{2\times 2} \\ B \end{bmatrix}, \qquad C_m = \begin{bmatrix} I_2 & 0_{2\times 12} \\ 0_{2\times 12} & C \end{bmatrix}^\top .$$

- To this end, the **infinite Kalman Filter** presented in the previous works has been recasted so to properly initialize the MPC open loop control problem (MPC-OLCP).

- Then, to properly formulate the MPC-OLCP, the following notation is introduce:
  - T_p : the prediction horizon.
  - T_c (being $T_c \leq T_p$): control horizon.
  - $x_m(\cdot\,|t)$: the trajectory of x_m over the horizon.
  - $x_m(\rho|t)$ with $\rho \in (0, T_p]$: computed value of x_m at time t+ρ.
  - $(\cdot)^p$: the predicted trajectory.
  - $(\cdot)^a$:the assumed trajectory.

Ground-based telescope Tracking Control Architecture Desing (4/4)

INAF OSSERVATORIO ASTRONOMICO DI CAPODIMONTE

MPC-based Tracking Control Architecture:

Local Open-loop Optimal Control Problem:

At time instat t, find $u(t)$ by solving the following optimal control problem:

Cost Function

$$\min_{u^p(\cdot|t)} \int_t^{t+T_p} \left\| y_m^p(\rho|t) - \bar{y}(\rho|t) \right\|_Q + \left\| u^p(\rho|t) - \tilde{h}\left(x_m^p(\rho|t)\right) \right\|_R + \left\| y_m^p(T_p|t) - \bar{y}^a(T_p|t) \right\|_F d\rho \qquad (18a)$$

s.t.

Dynamics constraints

$$\dot{x}_m^p(\rho|t) = A_m x_m(\rho|t) + B_m\left(u_m^p(\rho|t) - \delta^p(\rho)\right) \qquad (18b)$$

$$y_m^p(\rho|t) = C_m x_m(\rho|t) \qquad (18c)$$

$$\delta^p(\rho) = \sum_{j=1}^{D} \sqrt{2\,\alpha\, S_\tau(f_j)\,\Delta f}\,\cos\left(2\,\pi\, f_j\, \rho + \phi_j\right) \qquad (18d)$$

Kalman Initialization

$$x_m^p(0|t) = \hat{x}_m(t) \qquad (18e)$$

Torque Constraints

$$u_m^p(\rho|t) \in [u_{min}, \quad u_{max}] \qquad (18f)$$

Terminal Constraints

$$y_m^p(T_p|t) = \bar{y}^a(T_p|t) - y^a(T_p|t) \qquad (18g)$$

$$u^p(T_p|t) = \tilde{h}\left(x_m^p(T_p|t)\right) \qquad (18h)$$

being $\tilde{h}\left(x_m^p(T_p|t)\right) = K_r\, \bar{y}^a(T_p|t) + K_f\, y_m^a(T_p|t) + \delta(T_p)$.

Ensure the feasability and optimality of the solution, hence, the fulfilment of the control objectives

Ensure the MPC Closed loop staibilty

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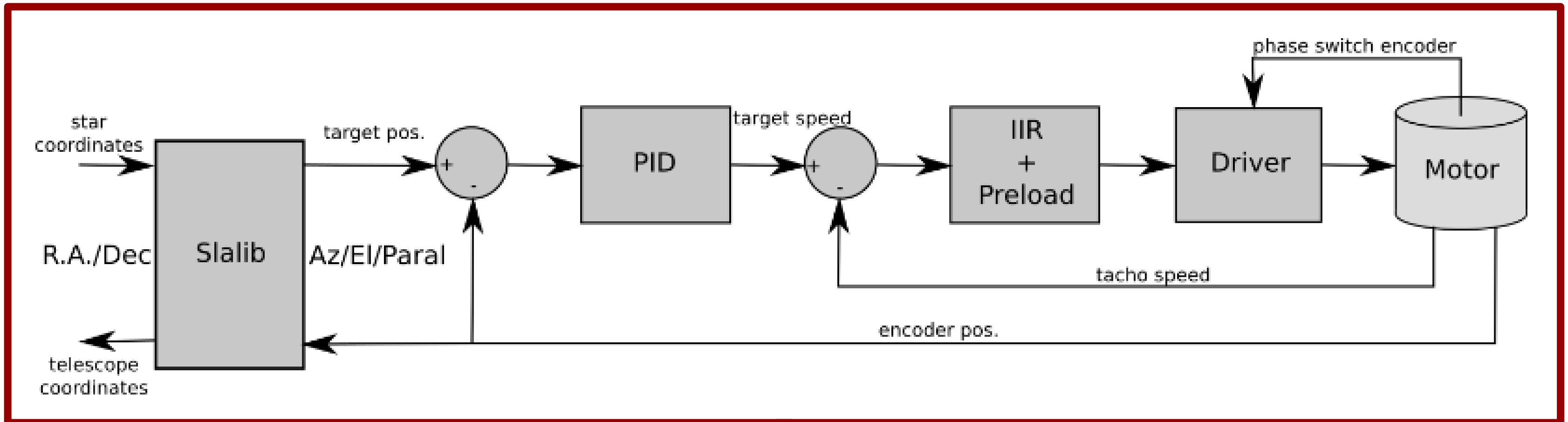
The Case of Telescopio Nazionale Galileo: TNG upgrading project (1/3).

Control Scheme Algorithm Upgrade

In oreder to test and validate the proposed approaches, the upgrading process of both hardware and software control architecture must be presented. Indeed, the folowing Fig. shown the running control scheme on the TNG.



The idea

The idea is to change it with the MPC-based control solution.

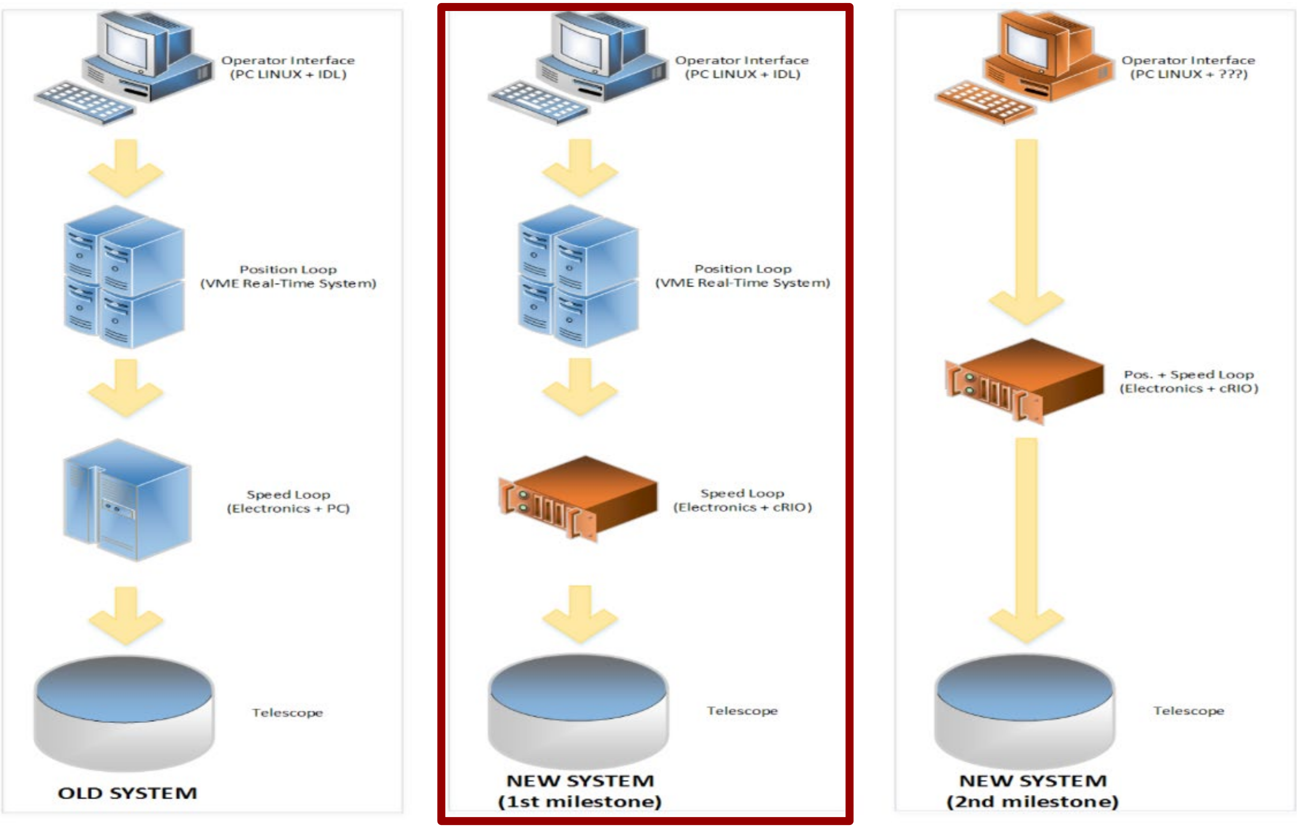
The upgrading process.

However, in the last year, the main objective was to upgrade the control hardware.

The Case of Telescopio Nazionale Galileo: TNG upgrading project (2/3).

Hardware Upgrade

Hardare upgrading process. From **[9]**.



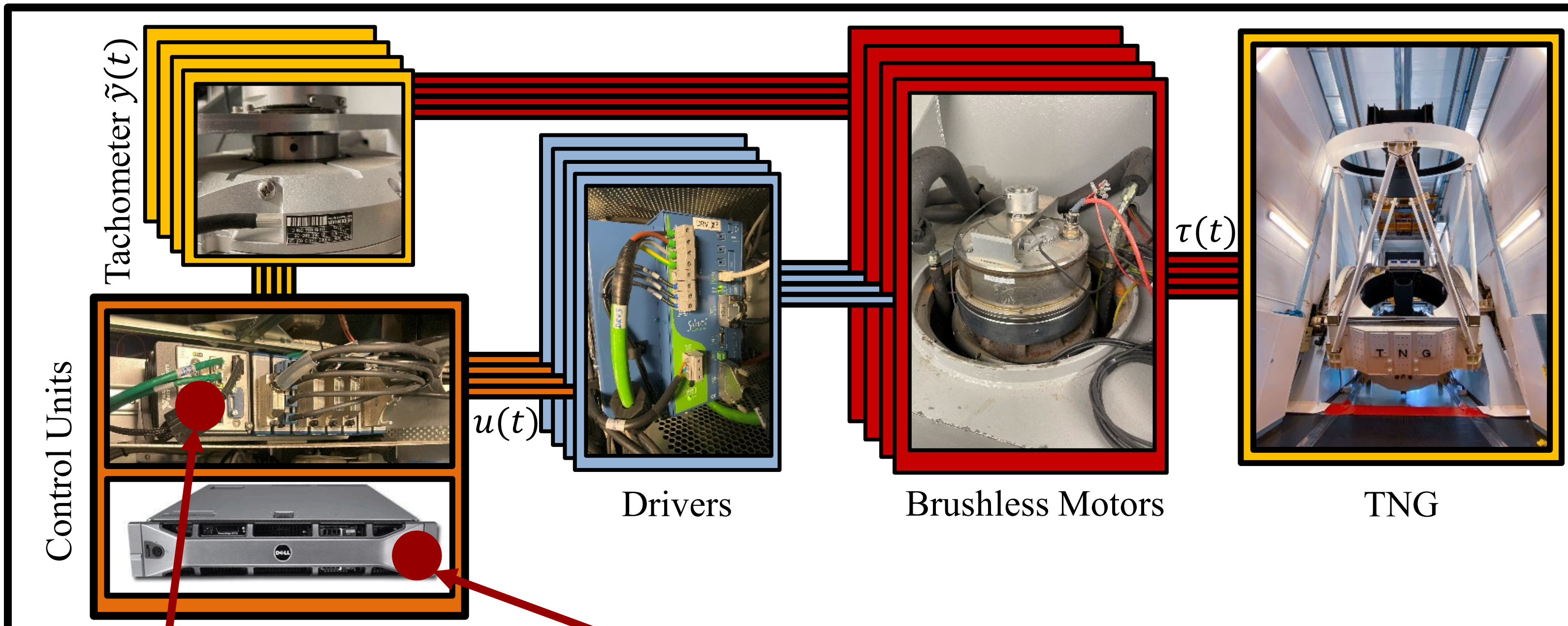
Here we are!

[9] Gonzalez, Manuel, et al. "Telescopio Nazionale Galileo control system upgrade." *Ground-based and Airborne Telescopes X*. Vol. 13094. SPIE, 2024.

The Case of Telescopio Nazionale Galileo: TNG upgrading project (3/3).

Hardware Upgrade

For each Axis



FPGA cRIO National Instruments

Dell PC Windows Server Running real-time Labview

The Case of Telescopio Nazionale Galileo: Simulation Results (1/5)

While the hardware update process finishes, first results have carried out in a simulative fashion.

Specifically, an advanced own made Matlab&Simulink platform has been developped

In this regards:

- **Indetification results:** we provide the identification results of the identified TNG model

- **Comparison Analysis:** to better highlight the advantages of the proposed control strategy, by performing the RMSE and the Tracking Index (TI) KPIs, a comparison analsysis w.r.t. the technical literature is provided.

The Case of Telescopio Nazionale Galileo: Simulation Results (2/5)

TNG Identification Results

- The data have been acquired by exciting the TNG real system via a mean zero white noise torque, at a sample time of 2 [ms] and recording the altitude and azimuth speed trends via the on-board equipped tachometers.
- The TNG dynamical system has been identified via the non-iterative subspace method.

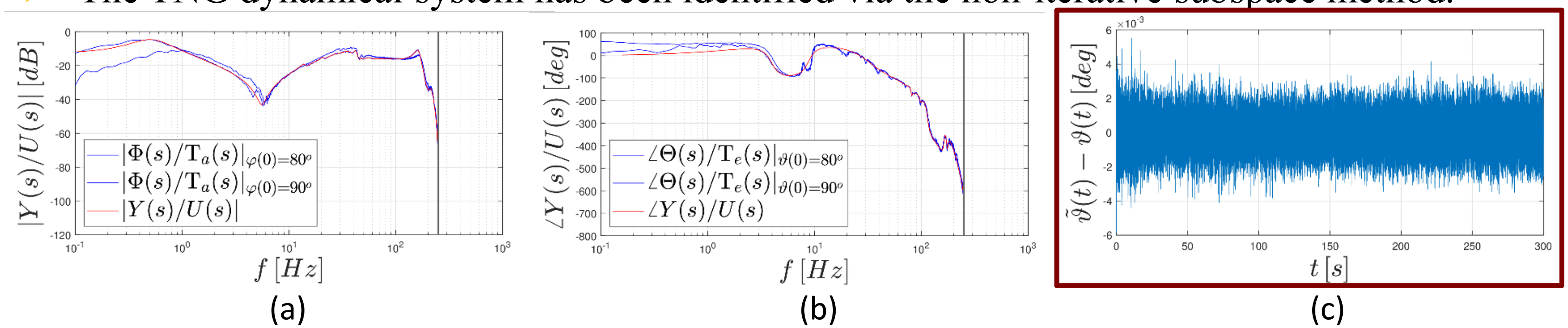


Fig.5: Altitude identification results. (a) magnitude; (b) phase; (c) prediction error.

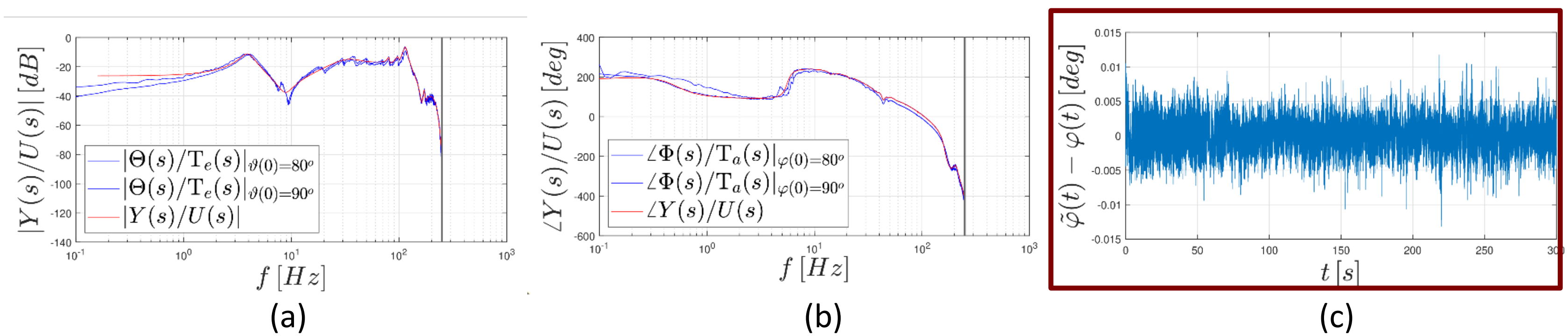
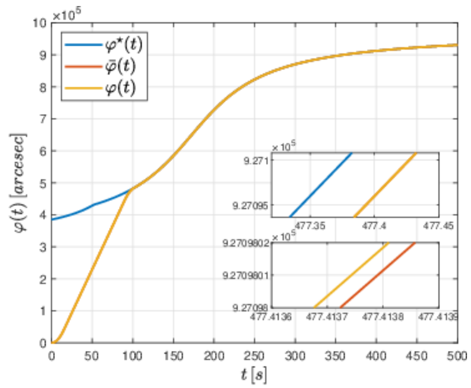
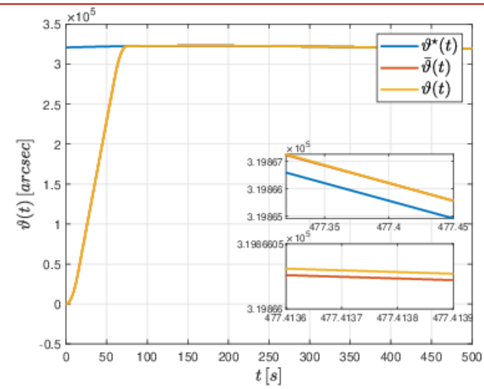
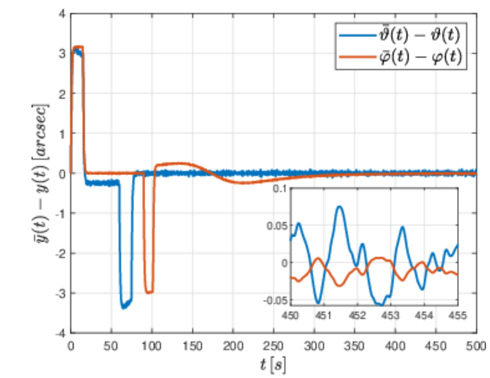
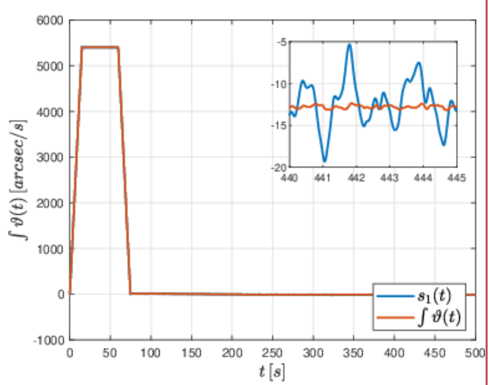
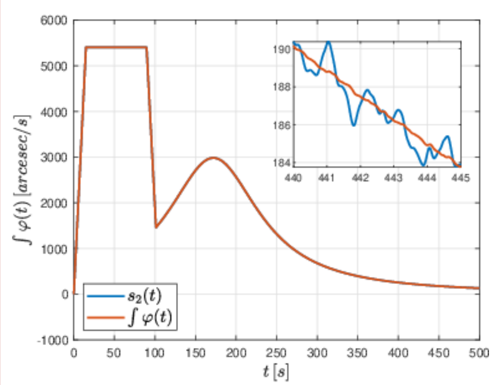
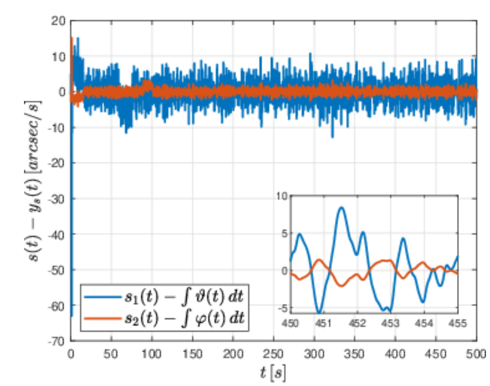


Fig.6: Azimuth identification results. (a) magnitude; (b) phase; (c) prediction error.

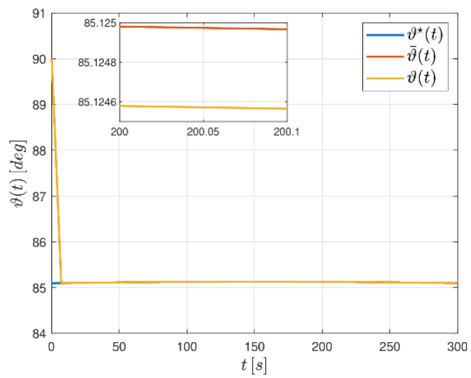
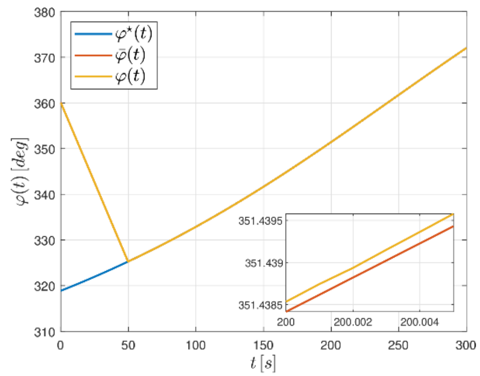
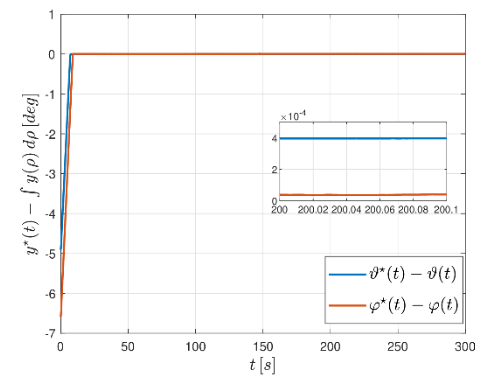
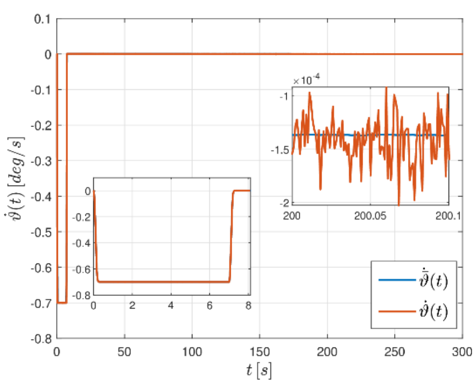
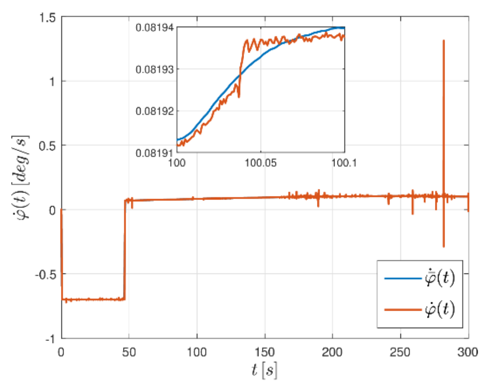
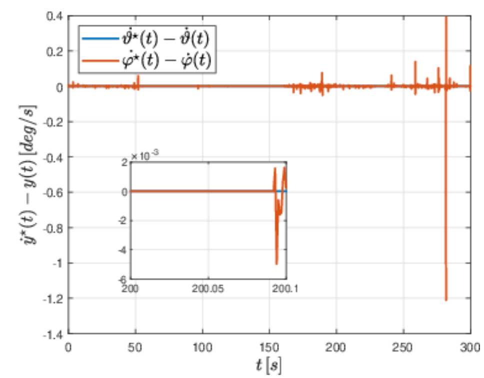
The Case of Telescopio Nazionale Galileo: Simulation Results (3/5)

Optimal Tracking Control Architecture Singularity Condition Scenario:

	Altitude axis	Azimuth axis	Error trends
Positions			
Speeds			

The Case of Telescopio Nazionale Galileo: Simulation Results (4/5)

MPC-based Tracking Control Architecture TYC 1731-916-1 Scenario:

	Altitude axis	Azimuth axis	Error trends
Positions			
Speeds			

The Case of Telescopio Nazionale Galileo: Simulation Results (5/5)

Comparison Analysis

Herein, we compare the tracking performance achievable via the proposed OTCA, the MPC-based appoach and the assested PID-based double loop architecture in **[10]**.

To dislose the tracking performance of the compared solutions, we consider 4 different pesudo star tracjetories, i.e. $\vartheta^{\star}(0) = (78^o, 82^o, 87^o, 89^o)$ and performe the RMSE and TI KPIs.

axis :		$\vartheta(t)$ $[arcsec]$				$\varphi(t)$ $[arcsec]$			
Configuration $\vartheta^{\star}(0)$:		78^o	82^o	87^o	89^o	78^o	82^o	87^o	89^o
MPC	TI	$6.24e^{-5}$	$6.24e^{-5}$	$5.99e^{-5}$	$5.99e^{-5}$	0.125	0.125	0.1164	0.1164
	RMSE	$1.02e^{-4}$	$1.13e^{-4}$	$2.92e^{-4}$	$2.92e^{-4}$	$2.26e^{-4}$	$2.47e^{-4}$	$2.11e^{-4}$	$2.11e^{-4}$
LQG-PI	TI	100.88	94.655	91.257	98.632	12.245	11.762	11.259	9.422
	Improvement	-99.99%	-99.99%	-98.63%	-98.63%	-98.97%	-98.93%	-98.97%	-82.65%
	RMSE	0.0084	0.0082	0.0084	0.0191	0.0084	0.0082	0.0084	0.0191
	Improvement	-87.85%	-86.21%	-96.52%	-98.90%	-97.30%	-96.98%	-97.49%	-98.90%
PID	TI	75.438	71.121	66.962	72.657	47.545	46.874	43.676	34.021
	Improvement	-99.99%	-99.99%	-99.99%	-99.99%	-99.73%	-99.73%	-99.73%	-99.66%
	RMSE	0.0266	0.0278	0.0278	0.0313	0.0266	0.0278	0.0278	0.0313
	Improvement	-96.16%	-96.33%	-98.95%	-99.07%	-99.15%	-99.11%	-99.24%	-99.33%

[10] MacMynowski, C. Blaurock, and G. Angeli, *"Initial control results for the thirty meter telescope"*, in AIAA505Guidance, Navigation, and Control Conference and Exhibit.

Conclusions:

In conclusion, in this Thesis we have:

- Formalized and addressed the optimal tracking control problem for a ground-based telescope in the presence of noise measurements and external disturbances.

- Proposed two optimal based tracking control architecture, i.e. the OTCA and the MPC-based tracking architecture, which embeds trajectory generator for ensuring the telescope's physical constraints and an Kalman filter to deal with measurement noise.

- The solution has been tailored for the TNG telescope whose dynamical behaviour has been identified via the non-iterative subspace approach.

- The effectiveness of the proposed solutions has been disclosed via virtual simulation, carried out via an own-made Matlab&Simulink platform also involving a comparison results w.r.t. the state-of-art control strategies

Future works:

i. Improvement of the identification procedure.
ii. Extension of the own-realized Matlab-based simulation platform by including dedicated modules emulating the TNG sensors behaviour and limitations.
iii. Test and validation of the proposed solutions on the real TNG telescope.

THANK YOU
for your
ATTENTION!