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Adaptive optics control with predictive controllers based on frozen-flow models for Low-Earth Orbit satellite tracking

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Abstract: We evaluate the performance of LQG predictive controllers built on auto-regressive dynamical zonal models of order 2 in the case of Low Earth Orbit satellite tracking case. We show thanks to end-to-end simulations that impressive performance improvement can be obtained with respect to the standard integral action regulator. Robustness results to errors on wind profile prior are also presented.

1. Introduction

Satellite and debris imaging is nowadays an important topic of research, with several applications like space debris observation for space security, or ground-based satellite tracking systems [1] for observation, military purpose or for ground-to-space optical telecommunication. As for astronomy observation, the atmospheric disturbance introduces in these applications wavefront distortions which degrade image acquired on ground-based telescopes [2]. Adaptive optics (AO) systems allow to compensate these nefarious effects in real time, using deformable mirrors (DMs) inserted in the telescope optical path. Wavefront sensors (WFSs) provide discrete-time wavefront measurements used by a digital controller to compute the DMs commands in a control loop. There are delays between the WFS measurements and the application of corresponding DM commands, and the turbulent phase evolves significantly during the lag, limiting the efficiency of the phase correction. This phase evolution leads to a temporal error commonly named servo lag error, which is a major performance limitation of AO systems.

2. Predictive controllers

The most commonly used AO controller, the standard integral action regulator, is known to suffer from servo lag error. Predictive controllers based a prediction of the wavefront have been proposed to counteract the effect of delays, and are used to compensate altogether telescope vibrations, windshake and atmospheric turbulence, see, e.g., [3–6]. In applications dealing with very fast dynamics of the disturbance, like Low Earth Orbit (LEO) satellite tracking systems where the satellite motion initiates very important apparent wind speeds on high altitude turbulent layers, predictive controllers are of great interest.

LQG regulators based on boiling turbulence models in Zernike basis using auto-regressive models of order order 2 (AR2) have been already successfully tested on sky [5]. In order to have a simpler representation of the turbulence evolution under Taylor frozen flow hypothesis [2] taken into account through a multi-layer atmosphere model, several approaches in zonal basis have been proposed for multi-conjugate AO (MCAO) [7] or multi-object AO (MOAO) [8].

3. LQG regulator based on AR2 zonal models for LEO satellite tracking

We propose in this presentation to evaluate the potential of AR2 dynamical resultant models in zonal basis proposed recently in the Single Conjugated AO case [9]. We thus evaluate the LQG control performance when using such dynamical models in the case of LEO satellite tracking systems similar to [10]. The performance will be evaluated for different positions of the satellite in the sky, with effects on the turbulent strength conditions and on the measurement noise of the Shack-Hartmann WFS from table 1. We compare the results with a standard integral action controller, and with LQG regulators from the literature. For a LEO satellite at 60 ° elevation angle, with then atmosphere parameters described in table 1, a quite bad turbulent condition of a 1.96" seeing and a good SNR on the WFS measurements, a performance improvement of almost 40 points of Strehl ratio at 0.80 μm can be obtained with comparison to the standard integral action controller as shown in table 2. Performance robustness to errors on the wind profile priors is also evaluated, and shows very reliable performance of the Zonal LQG AR2 regulator, opening then the way to experimentations on real systems.

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Telescope	Diameter: 1.8 m, Occultation: 20 cm
DM (Fried geometry)	17 x 17 with 265 valid actuators Gaussian influence function Coupling factor 0.3
Shack-Hartmann (supaberture grid)	16 x 16 with 204 valid subapertures Noise variance $\sigma_w^2 = 0.32$ rad^2
AO frame	2 kHz
λ_{wfs} & λ_{science}	0.55 μm & 0.80 μm

Layers (index)	Altitude (km)	Wind speeds (m/s)	Wind directions (°)
1	0	10	60
2	2	22.6	26.3
3	5	59.6	-12.6
4	7	70.9	0
5	10	101.3	0
6	12	121.5	0

Table 1. Left: LEO satellite tracking AO system parameters for end-to-end simulations. Right: LEO satellite tracking atmosphere parameters.

Regulator	State vector size	Strehl Ratio
Integral action	265	7.5 %
Zernike LQG AR2 from [5]	1720	24.5 %
Zonal LQG AR2	1978	47.4 %

Table 2. End-to-end simulation results with integrator, LQG AR2 based on a Zernike modelization of the phase and LQG AR2 zonal model.

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