European Journal of Control (2011)3:302–315

DOI:10.3166/EJC.17.302–315

European Journal of Control

Linear Quadratic Gaussian Control Applied to WFAO Systems: Simulation and Experimental Results

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Adaptive optics (AO) is a proven technique to correct turbulence on ground-based astronomical telescopes. The corrected Field of View (FoV) is however limited by the anisoplanatism effect. To extend the FoV, new Wide Field AO (WFAO) concepts have been recently developed. They aim at providing a wide FoV correction through the use of multi-guide-star WaveFront Sensors (WFSs) and several Deformable Mirrors (DMs). Such WFAO systems require a tomographic reconstruction of the atmospheric turbulence, leading to a multivariable problem of much higher complexity than in classic AO. They also raise new questions in terms of calibration and control. The Linear Quadratic Gaussian (LQG) control formalism is a natural way to cope with this issue. It enables both tomographic reconstruction and distinction between controlled output and measurements. In this paper, LQG control is presented and applied to WFAO systems. Performance is evaluated thanks to simulations based on theoretical studies, but also through laboratory experiments. We present the first results of the implementation of LQG control on a WFAO system, the HOMER bench, that has been developed recently at ONERA and which is devoted to WFAO laboratory research.

Keywords: Adaptive optics, optimal LQG control, tomographic reconstruction, wide field

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1. Introduction

Adaptive Optics (AO) [36] has been developed since 1970 for defence applications and applied, since the nineties, to astronomical telescopes. It is now also developed in many applications (laser beam focalisation, ophthalmology, military applications, optical communications ...). Astronomical AO is an original concept that aims at improving the angular resolution of ground based telescopes: the light coming from a Guide Star (GS), chosen for its intense brightness, is analyzed with a Wave Front Sensor (WFS). It is an optical device which measures the local slopes of a wave front. A Deformable Mirror (DM), conjugated with the pupil of the telescope, provides a correction in the direction of analysis. A computer receives as input the WFS data, and computes in real time the optimal DM shape so as to correct in closed-loop the turbulence distortion. The correction shape is then applied to the DM. Unfortunately, when we observe a star far from the GS, the performance of the system is degraded: this is the anisoplanatism effect, due to the fact that the light travels through different turbulent volumes depending on the angular distance from the center of the telescope Field of View (FoV). In order to compensate for this effect, the Multi-Conjugate AO (MCAO) concept has been proposed [3]: the turbulence is reconstructed and corrected in the volume, using several directions of analysis and several DMs, optically conjugated with different altitudes. The Corrected FoV (CFoV) is then increased compared to the

Received 15 January 2010; Accepted 30 September 2010
Recommended by E. Mosca, D.W. Clarke

classical anisoplanatic patch. Other related concepts, such as Ground Layer AO (GLAO) [35], Laser Tomographic AO (LTAO)[18] or Multi-Object AO (MOAO) [15] have also been proposed to increase the observable FoV. These concepts of Wide Field AO (WFAO) systems allow one to increase the CFoV but they are still under development because of their complexity. Contrary to AO, these systems indeed require the specification of a FoV where the correction has to be optimized, and thus involve tomographic reconstruction and correction.

Optimal tomographic reconstruction is well known in a static configuration, the solution being provided by a Minimum Mean Square Error (MMSE) estimator [12, 13]. But this solution is not adapted to closed-loop control. New approaches for reconstruction and control have been developed for WFAO systems [16, 22, 29, 33]. In particular, the Linear Quadratic Gaussian (LQG) approach has been proposed for AO systems starting in the early 90s [23, 27, 28]. In [20], it is shown that a discrete-time LQG control based on temporal averaged variables results in optimal performance of AO and WFAO systems (in the sense of minimum residual phase variance).

Recent theoretical and simulation results [22, 29, 31] suggest that LQG control is particularly suited to WFAO, where performance is to be optimized in directions that are distinct from directions of measurement. The key ingredient for LQG WFAO control is tomographic phase reconstruction using a Kalman filter. Also, implementing LQG controllers on those more complex systems (which feature several DMs and WFSs) raise challenging modeling and calibration issues that need to be addressed on realistic experimental test benches. In this paper, we present the first experiments in LQG WFAO control, on HOMER[1], the only existing wide-field test bench featuring LQG real-time control. Realistic end-to-end simulations and experiments on HOMER are performed, extending results in [9].

The paper is organized as follows. First, we recall the formalism of a classical AO system (Section 2) and we introduce the WFAO system's model and its specificity (Section 3). Optimal control formalism is then presented, followed by the main equations of LQG control (Subsection 3.2). In Section 4, we present simulation results obtained in HOMER configuration for two WFAO concepts: Tomographic AO (denoted in the following as NTAO for Natural TAO, which corresponds to LTAO without Laser GSs) and MCAO. The MCAO configuration allows us to compare the performance of LQG and integrator controllers. Finally, we present in Section 5 first experimental results of the implementation of an LQG control in NTAO configuration.

[1] HOMER (Hartmann Oriented Multi-Conjugate Experimental Resource) is an ONERA (Office National des Etudes et Recherches Aerospatiales) test-bench, dedicated to WFAO laboratory research for demonstration of new control approaches, which includes LQG control.

2. Classical AO Control

We recall in this section the main equations of a classical AO system, with only one DM and one WFS, as opposed to WFAO configurations in Section 3.

AO closed-loop systems provide real time correction of a turbulent wavefront using residual phase measurements. The block-diagram of an AO system is presented in Fig. 1. Phases are continuous-time variables, whereas control and measurements are discrete. The control $\mathbf{u}$ is applied to the DM through a Zero-Order Hold (ZOH) operating at sampling time T, so that $\mathbf{u}_n$ is the control applied at time nT. A discrete-time frame is therefore defined as a time interval of length T in the form $[nT, \ (n+1)T]$. DM and WFS operations are synchronized over the same sequence of sampling intervals $[nT, (n+1)T]$. More precisely, the WFS integrates the residual phase $\phi^{res} \triangleq \phi^{tur} - \phi^{cor}$ over one frame. Another frame is allocated for CCD camera read-out and slopes computation, all these operations corresponding to the WFS block, and control computation. This means that $\mathbf{u}_n$ is computed from the measurement $\mathbf{y}_n$, which corresponds to residual phase integration over $[(n-2)T, \ (n-1)T]$. Therefore, the total loop delay is two frames, see temporal diagram in Fig. 2. More complex temporal diagrams can also be considered [17, 24, 32, 34], where control application and WFS integration are not synchronized.

A widely used and relevant performance criterion to be minimized is the variance of the residual phase:

$$\mathbf{J}_c^{ao}(\mathbf{u}) = \lim_{t \to +\infty} \frac{1}{t} \int_0^t ||\phi^{res}(\tau)||^2 d\tau, \tag{1}$$

where $||.||$ is the Euclidean norm of the residual phase. In astronomy and in this paper, the major criterion of interest considered is the Strehl Ratio (SR). The SR can be defined as the ratio between the Point Spread Function (PSF) of the studied object in presence of turbulence, corrected or not, and the PSF of the telescope (without turbulence), the so-called Airy spot:

$$SR = \frac{\text{PSF}(\alpha)}{\text{Airy}(\alpha)}, \tag{2}$$

where α corresponds to the angular position of the object with respect to the center of the FoV. In classical AO, $\alpha = 0$. The better is the correction, the higher is the SR and the sharper and higher is the PSF. Minimizing the quadratic term $\mathbf{J}_c^{ao}$ is equivalent to maximize the coherent energy $E_c = exp^{-\sigma_{res}^2}$ [37]. Moreover, for small values of