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► To cite this version:

Nicolas Galland, Lucas Marquis, James Osborn, Henri-François Raynaud, Caroline Kulcsár. Auto-tuned AO control for all: design and simulation of an unsupervised LQG regulator in ORP project. COAT2023, COAT2023, Mar 2023, Durham, United Kingdom. 10.34693/COAT2023-009. hal-04604986

HAL Id: hal-04604986

<https://hal.science/hal-04604986v1>

Submitted on 13 Jun 2024

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Auto-tuned AO control for all: design and simulation of an unsupervised LQG regulator in ORP project

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ABSTRACT

In the framework of ground-based astronomical observation with large telescopes, the performance obtained in terms of image quality is strongly dependent on the quality of the adaptive optics (AO) system used. Among the recent work in this field, the development of new regulators (which compute the command applied to the deformable mirror to correct the incoming wavefront) is an approach that could be used to create the next generation of high-performance AO systems as well as a relatively easy way to upgrade existing systems. A particular example of such a controller is the Linear Quadratic Gaussian regulator that uses a model-based predictive approach to compute the DM commands. In the framework of the European H2020 ORP project, we propose to develop a fully auto-tuned and unsupervised LQG regulator to be implemented later on an existing AO system. The unsupervised procedure eliminates the need to manually do the calibration and embeds the auto-tuned part that updates the identified model and regulator parameters during observation. The goal is to allow astronomers to benefit for optimal AO control without the need for a control expert.

Keywords: Adaptive Optics, Linear Quadratic Gaussian controller

1. INTRODUCTION

The OPTICON Radionet Pilot project aims at providing access to many astronomical observation facilities throughout the world for the scientific community. As a part of this project, we propose to develop an unsupervised Linear Quadratic Gaussian (LQG) regulator that could be implemented on Adaptive Optics (AO) systems for various instruments. The main goal behind that idea is to provide access to an optimal AO correction without the need of a control specialist or a dedicated operator. In the following, we will briefly introduce the LQG regulator as we propose to implement it, present the preliminary simulation results that we obtained and discuss the foreseen work that we will do over the next 16 months.

2. GENERAL AO SETUP AND LQG CONTROLLER

Adaptive optics systems have been operating on telescopes since the middle of the 1990's¹ and have been continuously improved over nearly three decades. As a short reminder, a description of an AO system from a control point of view could be the following. Taking measurement from a wavefront sensor (WFS), a set of command voltages is computed by the regulator and applied to the deformable mirror (DM) that then corrects the incident turbulent phase of the beam which is seen by the WFS. Of course this is done with only a given portion of the incident photons, the rest being sent to the scientific instrument. The perfect correction corresponding to a flat phase should result in zeros measured by the WFS.

The regulator used on mostly every AO system in operation nowadays is an integrator (possibly leaky in order to increase robustness) whose formula is

$$u_k^{\text{INT}} = \alpha_{\text{leak}} u_{k-1}^{\text{INT}} - g M_{\text{com}} y_k, \quad (1)$$

where u is the voltage command vector, y is the slope vector obtained from the WFS, g a scalar gain, α_{leak} the leaking factor (generally a bit smaller than 1) and M_{com} the command matrix projecting slopes on the DM actuator space. Although robust enough, good performing and easy to implement, this controller has two main flaws:

- due to the WFS camera integration time (and calculation time that are usually of the same order of magnitude), the command that is applied at iteration k has in fact been calculated with slopes corresponding to input phase during iteration $k - 1$, introducing a large temporal error,
- although very good at rejecting usual atmospheric turbulence, this regulator may have trouble rejecting windshake and vibrations from real systems, and may even amplify it.

To overcome these problems, the use of Linear Quadratic Gaussian (or LQG) regulators is more and more investigated for AO implementations²⁻⁴. LQG is already implemented on some XAO systems to control a few low order modes (SPHERE, GPI). This kind of regulator addresses the two problems above by relying on a prediction of the turbulent phase. This prediction allows to compute the command corresponding to the future phase, thus reducing the temporal error. In addition, since this prediction is based on a modelization of the perturbation, it can take into account more complex ones than the atmospheric turbulence, including windshake and structure vibrations. The LQG command voltages are calculated by projecting the predicted phase $\hat{\phi}_{k+1}$ on the DM actuators space with

$$u_k^{\text{LQG}} = P_{\text{DM}} \hat{\phi}_{k+1}. \quad (2)$$

The prediction is obtained as the output of a Kálmán filter, based on a state space representation of the perturbation in the form

$$X_{k+1} = AX_k + V_k \quad (3)$$

$$\phi_k = C_\phi X_k \quad (4)$$

$$y_k = C_y X_k - M_{\text{int}} u_{k-d} + w_k \quad (5)$$

where X is the state vector, A is the state matrix, V is a white Gaussian noise, C_ϕ the matrix allowing to extract the phase from the state vector, C_y the measurement matrix, M_{int} is the system interaction matrix, d the total loop delay and w is the measurement noise. Using this state space representation, the Kálmán filter predicts the next occurrence of the state vector and thus the phase that will be used to compute the command. The Kálmán gain L_∞ is computed from the model and then used to recursively update the prediction:

$$\hat{X}_{k+1} = A\hat{X}_k + L_\infty(y_k - \hat{y}_k), \quad (6)$$

where $\hat{y}_k = C_y \hat{X}_k - M_{\text{int}} u_{k-d}$ are the predicted slopes values that can be obtained from the current predicted state vector. More information about the LQG controller in AO can be found in this reference.⁵

As it may appear from this description, such a controller is significantly more complicated to implement and tune than an integrator. However, the gain in performance and robustness that has already been observed on sky⁴ is we believe a strong enough motivation to pursue its implementation on other AO systems. It is to overcome this complexity and provide access to a high performance controller that we have proposed to implement an unsupervised auto-tuned LQG regulator for AO systems within the framework of the ORP project.

The first step of this work (still in progress) is to use this controller in simulations that will mimic as closely as possible the slowly evolving perturbations statistics of an AO system (atmospheric conditions as well as windshake and vibrations). By doing so, we want to test the update processes that will be necessary to achieve optimal performance throughout an observation night.

3. SIMULATION FRAMEWORK

The simulations performed during the prototyping phase are done using the Matlab software along with the OOMAO simulator package.⁶ This package uses the Object Oriented paradigm to perform all kinds of adaptive optics simulations. By using this framework for the first prototyping phase of our regulator, we will benefit from all previous developments done by the team regarding specific system features (segmented pupils, rotation, vibrations) as well as the model identification functions that will be used to compute the LQG matrices.

A representation of the generic simulation pipeline we are implementing is given in figure 1. The center part comprising the WFS, DM and LQG control computation is straightforward, using the objects of the OOMAO package.

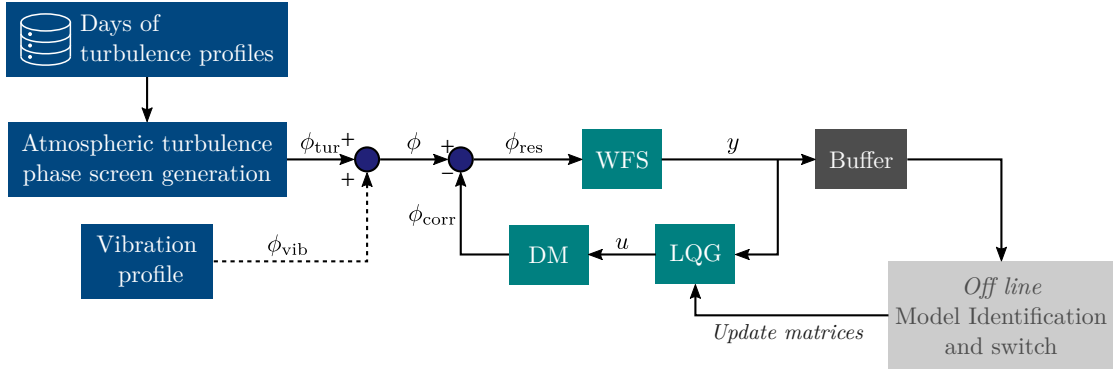


Figure 1. AO simulation flowgraph

The model identification functions have yet not been implemented within the simulation presented here, but were mainly developed and tested during L. Marquis' PhD thesis.⁷ They rely on statistical analysis of pseudo open-loop slopes to determine both the vibration low order characteristics and the atmospheric turbulence properties. This analysis as well as the state space description used by the LQG is here done with a Zernike based representation of the phase.

The addition of vibration has also not been done yet, and the following section focuses on the atmospheric turbulent phase screen generation.

We simulated two kinds of systems. The first tests have been done with a NAOS-like configuration with a 8.2 m circular pupil. We then concentrated on a more recent system with a GTCAO-like configuration which has a 11.35 m segmented pupil.

4. SIMULATING VARYING TURBULENCE

The atmospheric turbulence phase screens (ATPS) generation during the simulations is one of the key sub-process that we need to address in order to design our unsupervised regulator. We have first focused concentrated on simulating what we call turbulence bursts, where for a short period of time the seeing conditions brutally degrades dramatically. This kind of events help us verifying the robustness of the controller.

The second feature we began to implement in our simulation is the generation of ATPS with slowly varying spatio-temporal characteristics.

4.1 Turbulence bursts

To simulate a change in global r_0 for the resulting phase screen, the standard way is to multiply the phase by a scalar factor. By doing so, we keep the statistical correlations but change the overall turbulence strength. The factor α_ϕ that needs to be applied to change the turbulence from r_0^{init} to r_0^{final} is given by the following formula:

$$\alpha_\phi = \left(\frac{r_0^{\text{final}}}{r_0^{\text{init}}} \right)^{-5/6}. \quad (7)$$

By applying this factor with an arbitrary value and time dependence, the turbulence strength seen by the system is modified. In particular, we focus here on turbulence bursts that correspond to a sudden sharp drop of r_0 . Under such conditions, the closed-loop performance is dramatically lowered and the loop opens. We are then interested in recovering the previous performance level after this burst.

Figure 2 illustrates the effect of such a burst in two different cases. In the VLT case, we can see that the integrator recovers slowly to reach maximal performance after 1.5 s, whereas the LQG is almost instantaneously going back to optimal performances. In the GTC case, where the actuator density in the telescope pupil is a bit higher, both integrator and LQG recover fast after the burst (integrator being faster by a few iterations), but the LQG displays slightly better performance with a higher stability. In both cases, the LQG uses a very simple model with no refined tuning, yet still outperforms the integrator performance.

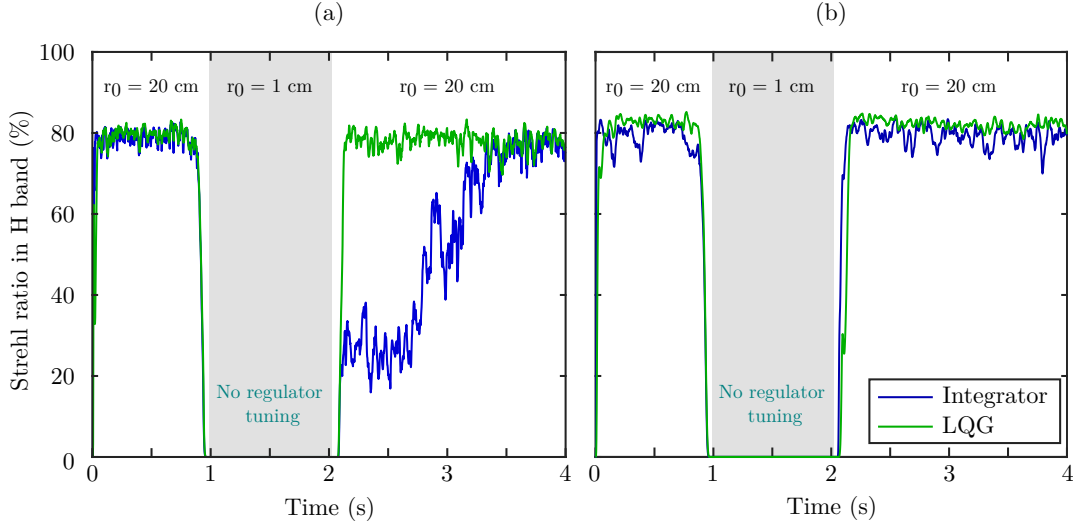


Figure 2. Effect of a strong turbulence burst simulated for two different telescope cases : (a) a VLT case with 185 actuators on a 8.2 m pupil (NAOS-like system) and (b) a GTC with 373 actuators in a 11.35 m pupil (GTCAO-like system). Both loops are running at 500 Hz with the same turbulence conditions.

4.2 Long term variations

The design process of an autotuned regulator which should be able to operate without supervision during a complete observation night requires to take into account the slow variation of atmospheric turbulence characteristics. To do so, we will include in our simulation the possibility to modify on the fly the spatio-temporal characteristics of the turbulent phase using data measured on sky by the Durham University team.^{8,9} In short, these data files contain a description of the atmosphere statistics in the form of a 100 layer description sampled about every minute. For each time stamp, the value of global r_0 , seeing, coherence time, anisoplanatic angle and scintillation index are given along with the 100 layers profile (with 250 m resolution), the C_n^2 , wind speed and the wind direction.

As a core feature of OOMAO, the ATPS generating object will take these parameters into account to create a time sequence of phase screens matching these characteristics. The difficult part here is that there is no possibility to modify these parameters on the fly while ensuring a smooth evolution of the spatio-temporal properties.

The solution we decided to implement is to simulate two phase screens. The first one is generated with the turbulence characteristics measured at a given timestamp, the other one with the turbulence characteristics of the next measured profile in the data file. These screens are then merged into a resultant phase using a time varying gain that ensures that the variance of the resultant screen evolves smoothly between those of the two individual ones.

Figure 3 shows the time evolution of the spatial variance of the turbulent phase within the pupil. In addition to the calculation described above, this figure displays the jumps at 1 s and 2 s corresponding to the change of characteristics for phase screens 2 and 1 respectively. These jumps have no effect on the resultant variance as they happen to the statistics of a screen that does not contribute to the mixing at this moment. The transitions between phase screens 1 and 2 can be slower or faster depending on a chosen transition profile. We can then use an arbitrary number of profiles from the data without the need to re-scale our simulation as two phase screen generators are enough. Although the total duration shown here is a lot smaller than 1 minute, it was enough to validate the process that will be used in long (a few minutes or tens of minutes) simulations.

5. PERSPECTIVES

The preliminary work presented above represents the first step of the development of our unsupervised regulator. The next step will be to implement the model identification processes that has been developed by the team over

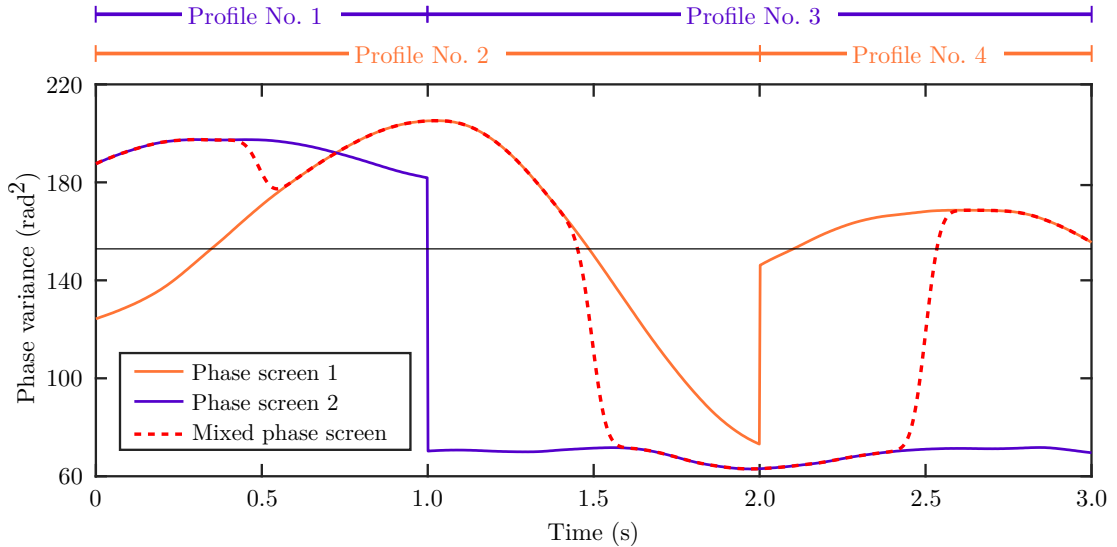


Figure 3. Generation of a resultant phase screen by mixing two separately generated screens with a time varying gain. The dashed red line is the spatial variance of the resulting screen, the plain dark purple and light orange discontinuous curves represent the variance of the separately generated screens.

the past years and determine how often this should be triggered (or following which indicator) to ensure the continuity of optimal performances.

Concerning the disturbance, it will be necessary to include vibrations and windshake in the simulations as they are key factors that make the LQG controller appealing. Furthermore, as we wish to implement such controllers on large telescopes which often have a segmented non-circular pupil, the rotation effect will have to be considered. These two aspects have already been investigated during L. Marquis' PhD thesis but have not been implemented in addition to the long term evolving atmospheric turbulence.

From a software implementation point of view, it will be required to clearly define the interfaces with both the AO systems and the user. This includes among other things the adaptation of the implementation according to the RTC (data format, structures, ...), the relevant performance indices that the end user might want to have access to and that the system itself requires to ensure optimal performances, the tuning parameters that the user might act upon if needed.

Concerning the project, it would be both interesting and useful to implement the designed regulator on a real AO system to confront to on-sky operation and, if needed, refine some aspects of the implementation. An implementation within the COSMIC+COMPASS framework, which is already operating on existing systems (such as the KECK observatory) and is foreseen to be used for next generation instruments, would be of interest.

ACKNOWLEDGMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme (ORP project) under grant agreement No 101004719

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