Real-time implementation of an LQG tip-tilt controller for regular science observation on GeMS

Gaetano Sivo, Rémy Juvénal, Caroline Kulcsár, Vincent Garrel, Pedro Gigoux, Henri-François Raynaud, Eduardo Marin, Jean-Marc Conan, Cyril Petit, William Rambold, et al.

Gaetano Sivo, Rémy Juvénal, Caroline Kulcsár, Vincent Garrel, Pedro Gigoux, et al.. Real-time implementation of an LQG tip-tilt controller for regular science observation on GeMS. SPIE Astronomical Telescopes + Instrumentation, Adaptive Optics Systems V, SPIE, Oct 2016, Edimbourg, United Kingdom. pp.99094Y, 10.1117/12.2233191 . hal-01722330

Real-time implemenation of an LQG tip-tilt controller for regular science observation on GeMS

Gaetano Sivo[a], Rémy Juvénal[b,c], Caroline Kulcsár[b], Vincent Garrel[a], Pedro Gigoux[a], Henri-François Raynaud[b], Eduardo Marin[a], Jean-Marc Conan[c], Cyril Petit[c], William Rambold[a], Vanessa Montes[a], Cristian Moreno[a], Jeff Donahue[d], Rodrigo Carrasco[a], Marcos van Dam[e], Benoit Neichel[f], Lucie Leboulleux[g], and Chad Trujillo[d]

[a]Gemini South Observatory, La Serena, Chile;
[b]Institut d'Optique Graduate School, Laboratoire Charles Fabry, Palaiseau, France;
[c]Onera, The French Aerospace Lab, Châtillon, France;
[d]Gemini North Observatory, Hilo, Hawaii, USA;
[e]Flat Wavefront, Christchurch, New Zealand;
[f]Laboratoire d'Astrophysique de Marseille, Marseille, France;
[g]former Gemini Observatory

ABSTRACT

AO systems aim at detecting and correcting for optical distortions induced by atmospheric turbulences. They are also extremely sensitive to extraneous sources of perturbation such as vibrations, which degrade the performance. The Gemini South telescope has currently two main AO systems: the Gemini Multi Conjugated AO System GeMS and the Gemini Planet Imager GPI. GeMS is operational and regularly used for science observation delivering close to diffraction limit resolution over a large field of view (85×85 arcsec^2). Performance limitation due to the use of an integrator for tip-tilt control is here explored. In particular, this type of controller does not allow for the mitigation of vibrations with an arbitrary natural frequency. We have thus implemented a tip-tilt Linear Quadratic Gaussian (LQG) controller with different underlying perturbation models: (*i*) a sum of autoregressive models of order 2 identified from an estimated power spectrum density (s-AR2) of the perturbation,[1] already tested on CANARY[2] and routinely used on SPHERE;[3] (*ii*) cascaded ARMA models of order 2 identified using prediction error minimization (c-PEM) as proposed in.[4,5] Both s-AR2 and c-PEM were parameterized to produce tip or tilt state-space models up to order 20 and 30 respectively. We discuss the parallelized implementation in the real time computer and the expected performance. On-sky tests are scheduled during the November 2016 run or the January 2017 run.

Keywords: Adaptive Optics, Multi-Conjugated Adaptive Optics, GeMS, Optimal Control, Kalman Filter, Vibrations Rejection, LQG

1. INTRODUCTION

In the near future, several new telescopes will look at the sky reaching extremely large pupil diameter such as the Thirty Meter Telescope (TMT),[6] the European-Extremely Large Telescope (E-ELT),[7] or the Giant Magellan Telescope (GMT).[8] These systems cannot be conceived without using Adaptive Optics (AO). An AO system allows to analyze the incoming wavefront in real-time and corrects for it. The main problem of classical AO is the limitation of the corrected field of view. To encounter this issue, other concepts of AO working in a much wider field of view (WFAO) have been proposed and developed, such as Laser Tomographic AO (LTAO),[9] Ground Layer AO (GLAO),[10] Multi-Object AO (MOAO),[11] or Multi-Conjugated AO (MCAO).[12]

The Gemini South Telescope has an MCAO facility that aims to deliver close to diffraction limit images on a 2′ field of view (FoV). The system is the Gemini Multi-Conjugated AO System (GeMS).[13,14] Like every AO systems,

---

Further author information: (Send correspondence to Gaetano Sivo)
Gaetano Sivo: E-mail: gsivo@gemini.edu, Telephone: +56 51 2205 642

Adaptive Optics Systems V, edited by Enrico Marchetti, Laird M. Close, Jean-Pierre Véran, Proc. of SPIE Vol. 9909, 99094Y

· doi: 10.1117/12.2233191

it needs to be driven by a controller. The controller currently implemented in the real-time computer (RTC) for the tip and tilt modes is an integral action controller. However, for such a system, an optimal controller, the Linear Quadratic Gaussian controller, could be envisionned and implemented. This type of controller estimates and predicts the distorted phase from the incident wavefront. In the past decade, studies in simulations, in lab and on-sky have been conducted and done with great success. It has been demonstrated that it delivers better performance on the instrument CANARY,[2] SPHERE[3] and GPI.[15] This controller seems particularly adapted in the case of presence of other perturbations than atmospheric turbulence, such as mechanical vibrations.[2, 3, 15]

In this paper we present briefly the LQG controller. Then we present the performance obtained using this controller on simulatons based on on-sky data and we finally present the implementation strategy adapoted in the RTC and the operational model.

2. THE GEMINI MCAO FACILITY

The Gemini MCAO system GeMS[13, 14] is the AO facility built for the Gemini South Telescope located on top of the Cerro Pachón in Chile. As every MCAO instrument, GeMS works in closed loop. The incoming perturbation (here atmospheric turbulence) is reconstructed in a volume thanks to measurements coming from 5 Sodium laser guide stars using 5 16×16 Shack-Hartmann wavefront sensors (giving 204 valid subapertures composed by a 2×2 pixels) and up to 3 natural guide stars for tip-tilt sensing using an APD-based quadcells wavefront sensor. Each of the APDs give 2 independant measurements (one tip and one tilt per APD) and the averages of the measurements available allow to compute a voltage command that will be applied on the Tip Tilt Mirror for tip-tilt compensation. We propose to modify the controller used to determine these voltages by using an LQG controller that has demonstrated to increase the performance on other systems on-sky[2, 3, 15] and on simulations for GeMS using GeMS on-sky data.[5, 16] A detailed proceeding in this conference has been presented to explain the current status of GeMS and all the upgrades scheduled to improve the status and where we are regarding their execution.[17]

3. LQG CONTROL FOR TIP-TILT CORRECTION: TURBULENCE AND VIBRATIONS

The Linear Quadratic Gaussian (LQG) AO control technique can be used not only for atmospheric turbulence correction but also to compensate for additional perturbations such as vibrations due to the telescope environment. The generical aspect of this contoller makes this easy in the formalism. This controller has been demonstrated in lab and on-sky with the CANARY pathfinder and showed very good results and improvements in term of performance.[2, 18–20] This controller is as well now used in regular operation on the extreme AO system SPHERE at the Very Large Telescope[3] and GPI[15] at the Gemini South Telescope.

In this section, we present the procedure of the LQG control, that has been tested on several dataset acquired on-sky using the GeMS system in Fall 2015. Because the image quality is directly linked to the residual phase variance defined as below:

$$\Phi^{\mathrm{res}} \triangleq \Phi - \Phi^{\mathrm{cor}}. \tag{1}$$

The goal is here is to minimize the criterion $\mathcal{J}_c(u)$ defined as:

$$\mathcal{J}_c(u) \triangleq \lim_{T' \to +\infty} \frac{1}{T'} \int_0^{T'} ||\phi^{\mathrm{res}}(t)||^2 \,\mathrm{d}t = \lim_{T' \to +\infty} \frac{1}{T'} \int_0^{T'} ||\phi(t) - \phi^{\mathrm{cor}}(t)||^2 \,\mathrm{d}t \tag{2}$$

where Φ^{cor} is the correction phase and is equal to Nu with N being the TTM influence matrix and u the vector of commands (in voltages) that is sent to the TTM actuators. The LQG controller can be implemented is the 3 statements given below are stated:

- the system is linear;
- the criterion to minimize is quadratic
- the noises have Gaussian distributions and the covariance matrices are known.

Since the mirror response is really fast compared to the sampling time T and applied through a zero order hold, we can model the system using a discrete time configuration with a sampling period T in order to obtain the optimal control without making any approximations.[21] In this discrete time framework, the continuous criterion given in (Eq. 2) can be rewritten by the following:

$$\mathcal{J}(u) = \lim_{K \to +\infty} \frac{1}{K} \sum_{k=1}^{K} ||\phi_{k+1} - N u_k||^2. \tag{3}$$

The optimnal solution that minimizes this criterion is:

$$u_k^* = P_u \widehat{\Phi}_{k+1|k} \tag{4}$$

where the optimal prediction $\widehat{\Phi}_{k+1|k}$ is an output of a Kalman filter and where the projection onto the DM space is obtained here using:

$$P_u = N^\dagger = M_{\text{com}} D. \tag{5}$$

The optimal estimated phase $\widehat{\Phi}_{k+1|k}$ is defined as:

$$\widehat{\Phi}_{k+1|k} \triangleq \mathrm{E}[\Phi_{k+1} | y_k, \ldots, y_0] \tag{6}$$

where Φ has to be defined as the output of a state model.

3.1 STATE SPACE MODEL

For every tip ot tilt mode represented hereafter by the symbol $\bullet$, we can define a state vector named $x_k^\bullet$:

$$x_k^\bullet \triangleq \begin{pmatrix} \Phi_k^{\text{tur},\bullet} \\ \Phi_{k-1}^{\text{tur},\bullet} \\ \Phi_k^{\text{vib},1,\bullet} \\ \Phi_{k-1}^{\text{vib},1,\bullet} \\ \Phi_k^{\text{vib},2,\bullet} \\ \Phi_{k-1}^{\text{vib},2,\bullet} \\ \vdots \\ \Phi_k^{\text{vib},n_{\text{vib}},\bullet} \\ \Phi_{k-1}^{\text{vib},n_{\text{vib}},\bullet} \end{pmatrix} \tag{7}$$

where n_{vib} is the number of vibrations that we want to identify and reject. To evaluate the estimated phase, we need a model that describes the evolution of the perturbation Φ, together with a measurement model, that are defined below:

- The state equation describing the evolution of the state vector is:

  $$x_{k+1} = A x_k + v_k, \tag{8}$$

  where v is a white Gaussian noise with a covariance matrix Σ_v and A describes the dynamics of the perturbations.

- The observation equation describing the measurments is:

  $$y_k = C x_k - M_{\text{int}} u_{k-2} + w_k = D\Phi_{k-1} - DN u_{k-2} + w_k, \tag{9}$$

  where w is a white Gaussian noise independant from v and with a covariance matrix Σ_w.

To compute the matrix A, we need a description of the atmospheric turbulence. We have chosen here the temporal dynamics of the turbulence with an auto-regressive model of order 2 (AR2):[22–24]

$$\Phi_{k+1}^{\mathrm{tur}} = A_1^{\mathrm{tur}}\Phi_k^{\mathrm{tur}} + A_2^{\mathrm{tur}}\Phi_{k-1}^{\mathrm{tur}} + v_k^{\mathrm{tur}}, \tag{10}$$

where v_k^{tur} is a white Gaussian noise and A_1^{tur} and A_2^{tur} are diagonal matrices. These 2 matrices depend on physical parameters, a dumping coefficient, a reasonant frequency and the power (excitation noise variance).

We use the exact same type of model to describe the evolution of the vibrations. Every vibratory components are described using a dedicated AR2 model:[1, 2, 25, 26]

$$\Phi_{k+1}^{\mathrm{vib}} = A_1^{\mathrm{vib}}\Phi_k^{\mathrm{vib}} + A_2^{\mathrm{vib}}\Phi_{k-1}^{\mathrm{vib}} + v_k^{\mathrm{vib}}. \tag{11}$$

The perturbation phase Φ can be evaluated as the sum of turbulence and vibratory components:

$$\Phi = \Phi^{\mathrm{tur}} + \sum_{i=1}^{n_{\mathrm{vib}}} \Phi^{\mathrm{vib},i}. \tag{12}$$

Because for GeMS we consider only tip and tilt, we can separate their model constructions and implementations and write:

$$\forall \bullet \in \{\mathrm{tip}, \mathrm{tilt}\} \qquad \Phi^{\bullet} = \Phi^{\mathrm{tur},\bullet} + \sum_{i=1}^{n_{\mathrm{vib}}} \Phi^{\mathrm{vib},i,\bullet}. \tag{13}$$

3.2 KALMAN FILTER

Based on the state representation of the equations (8 and 9), where the matrix A is built from the equations (10 and 11) and he matrix C from the equations (9 through 12), the corresponding Kalman filter can be established. It consists of:

- An update equation:

  $$\widehat{x}_{k|k} = \widehat{x}_{k|k-1} + H_\infty(y_k - \widehat{y}_k), \tag{14}$$

  where H_∞ is the asymptotic Kalman gain. This equation brings the information coming from the last measurement y_k.

- A predictive equation:

  $$\widehat{x}_{k+1|k} = A\widehat{x}_{k|k}, \tag{15}$$

  where we estimate the new state vector according to the chosen model.

The asymptotic Kalman gain H_∞ is defined as:

$$H_\infty \triangleq \Sigma_\infty C^{\mathrm{T}}(C\Sigma_\infty C^{\mathrm{T}} + \Sigma_w)^{-1}, \tag{16}$$

where Σ_∞ is the solution of the discrete algebraic Riccati equation and is computed off-line.

3.3 REAL-TIME IMPLEMENTATION

Using the equations previously defined, we decided to implement the control loop as followed:

$$\forall \bullet \in \{\mathrm{tip}, \mathrm{tilt}\} \qquad \begin{array}{l} x_{k+1}^{\bullet} = M_1 x_k^{\bullet} + M_2 y_k^{\mathrm{res},\bullet} + M_3 u_{k-2}^{\bullet} \\ u_k^{\bullet} = M_4 x_k^{\bullet} \end{array} \tag{17}$$

The instructions that are implemented in the RTC are described below using a Matlab syntax. These instructions are the ones from the pseudo-code developed during the simulation studies.[5]

```
% Initialize all variables to zero
% Load all static parameters from file NgsLqg.mat into memory
nState = 32
%%%%%%%%%%%%%%%%%%%%%% LOOP BEGINS HERE %%%%%%%%%%%%%%%%%%%%%%%%
%      --> while loop is closed do
%%%%%%%%%%% Pseudo_RTC_GeMS_parallel.m starts here %%%%%%%%%%%

%% TIP % thread 1 computes Tip command
mateltCmndsXkTip = 0;
for ii=1:nState
    mateltCmndsXkTip = mateltCmndsXkTip+M3tip(ii)*pXk(ii);
end
U(1) = mateltCmndsXkTip+M4tip*pT(1);

%% TILT % thread 2 computes Tilt command
mateltCmndsXkTilt = 0;
for ii=1:nState
    mateltCmndsXkTilt = mateltCmndsXkTilt+M3tilt(ii)*pXk(nState+ii);
end
U(2) = mateltCmndsXkTilt+M4tilt*pT(2);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% -->  Send U to TT mirror %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% => TIP STATE PARTIAL VALUE 1
% thread 3
mateltXk = zeros(1,nState);
for jj=1:nState
    for ii=1:nState
        mateltXk(jj) = mateltXk(jj)+M1tip(jj, ii)*pXk(ii);
```

```
    end
end

%% =>TIP STATE PARTIAL VALUE 2
% thread 4
for jj=1:nState
    mateltpT(jj) = M2tip(jj)*pT(1);
end

%% ==> TIP STATE FINAL
% thread 5 needs the completion of threads 3 and 4
for jj=1:nState
    pK(jj) = mateltXk(jj) + mateltpT(jj);
end
pK(nState) = U(1);

%% => TILT STATE PARTIAL VALUE 1
% thread 6
mateltXk = zeros(1,nState);
for jj=1:nState
    for ii=1:nState
        mateltXk(jj) = mateltXk(jj)+M1tilt(jj, ii)*pXk(nState+ii);
    end
end

%% => TILT STATE PARTIAL VALUE 2
% thread 7
for jj=1:nState
    mateltpT(jj) = M2tilt(jj)*pT(2);
end
```

```
62
63 %% ==> TILT STATE FINAL
64 % thread 8 needs the completion of threads 6 and 7
65 for jj=1:nState
66     pK(nState+jj) = mateltXk(jj) + mateltpT(jj);
67 end
68 pK(2*nState) = U(2);
69
70 %% COMMANDS AND STATE UPDATE
71 pT=U
72 pXk=pK
73
74
75 %%%%%% Pseudo_RTC_GeMS_parallel.m ends here %%%%%%%%
76 %     If NgsLqg.mat has been modified, reload NgsLqg.mat into memory
77 %     ---> end (while loop is closed)
```

Thread 1 describe in lines 8 to 13 on the pseudo code presented above and thread 2 in lines 15 to 20 are independant and can be executed in parallel. Threads 3, 4, 6 and 7 are independant from threads 1 and 2 and are independant one from each other. Thread 5 needs only the completion of threads 3 and 4. Thread 8 needs only the completion of thread 6 and 7.

4. SIMULATONS RESULTS AND OPERATIONAL GUIS

4.1 GEMS DATA SETS

In order to perform the identification of the model describing the perturbation and thus being able to test several type of models used to feed the LQG control, we studied 70 data sets acquired on-sky using GeMS. These data have been acquired at a sampling frequency varying from 150 to 700Hz. Every buffers are filled with 8, 000 samples. On these data, we can see that strong vibrations affects the GeMS performance.[5,16]

4.2 PERFORMANCE EVALUATION

In this section, we compare the performance obtained with an integrator controller and an LQG controller. Then we compare the performance obtained different type of model to feed the LQG controller.

The results shown in figure (2) represents the performance obtained using an integral controller and the performance obtained using an LQG controller. These performance are obtained in the so-called replay mode. Indeed, we take the closed loop circular buffers acquired on-sky. Using the command values we can reconstruct the pseudo open loop (POL) measurements and we use this as inputs on our simulation code. The figure (1) describes the procedure adopted in the simulation.

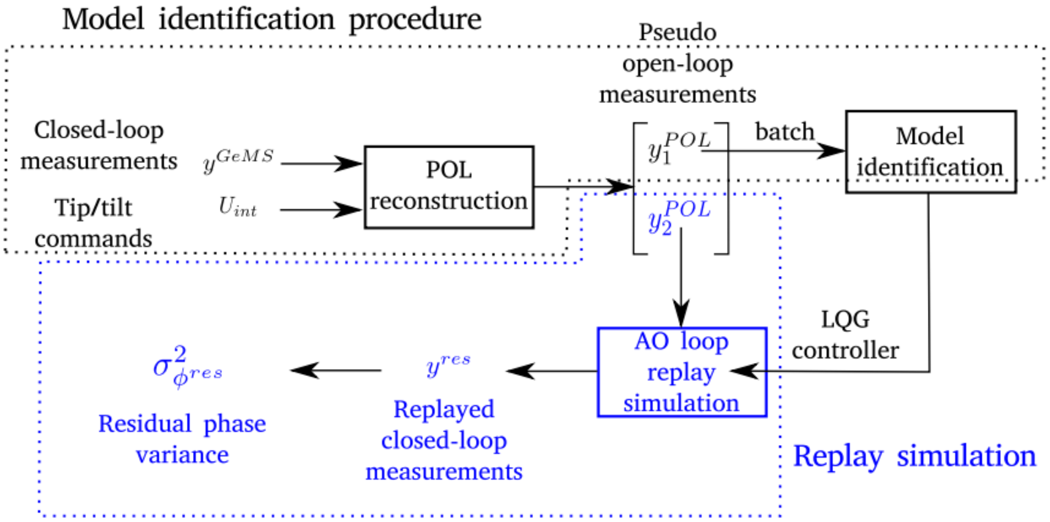


Figure 1. Performance analysis procedure.

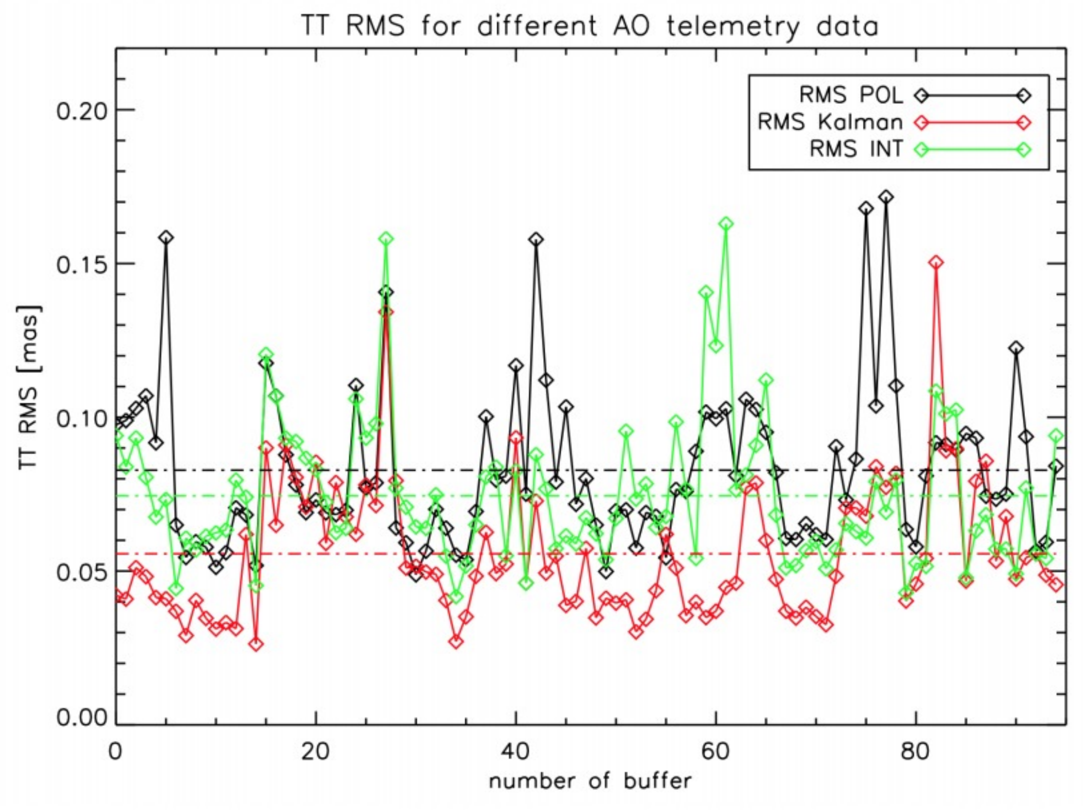


Figure 2. Performance analysis procedure.

The results presented in the figure (2) give for every circular buffer we have available in abscisse the RMS values of the POL temporal sequence and its resulting residual phase after using an LQG controller rejecting 10 identified vibratory components. On average on all the circular buffers, the mean POL RMS value is 82.9mas, when the mean value of the residual phase after closing the loop with an LQG contoller goes down to 55.6mas. Now if we use a standard integral controller, the residual phase is about 72mas. We can clearly see a gain in term of improvements.

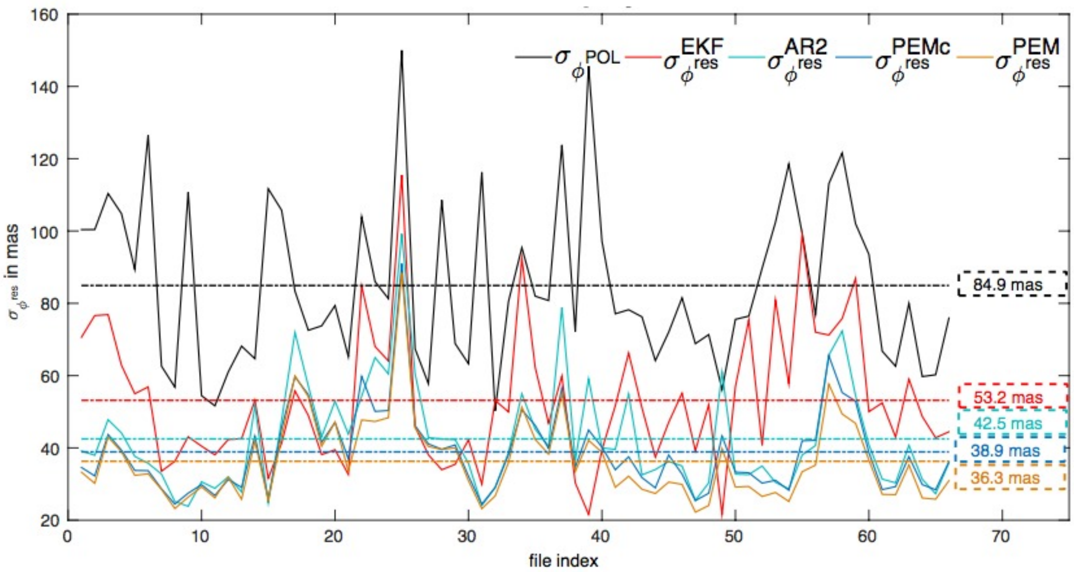
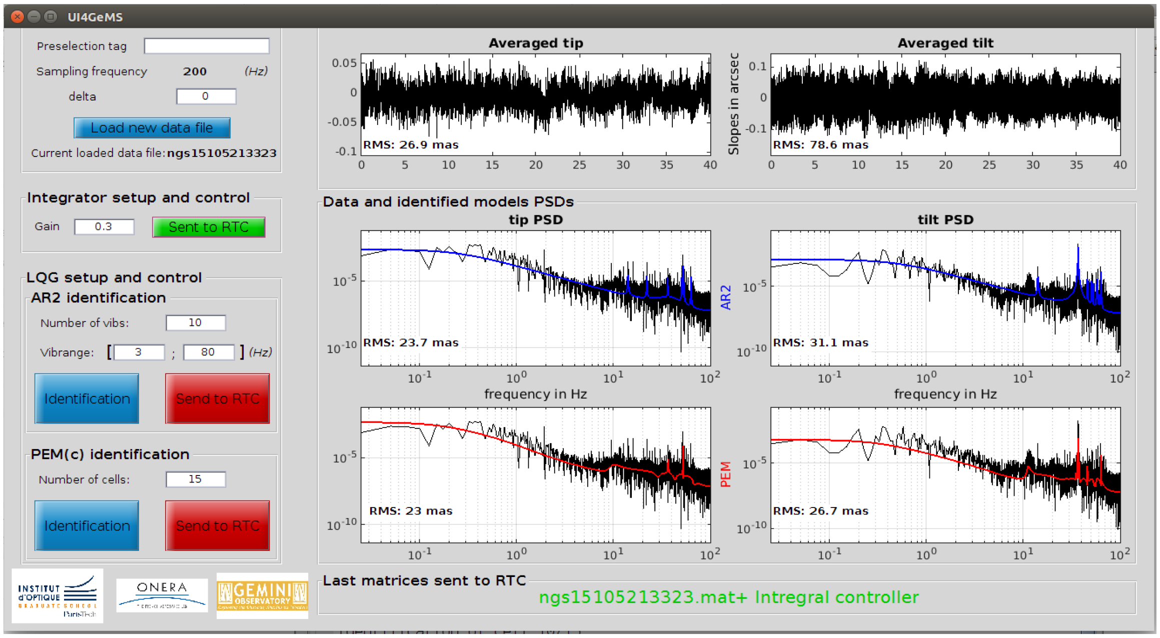


Figure 3. Performance of different model used to build the LQG controller.


UI4GeMS

Preselection tag

Sampling frequency 200 (Hz)

delta 0

Current loaded data file: ngs15105213323

Integrator setup and control

Gain 0.3

LQG setup and control

AR2 identification

Number of vibs: 10

Vibrange: [3 ; 80] (Hz)

PEM(c) identification

Number of cells: 15

Last matrices sent to RTC

ngs15105213323.mat+ Intregral controller

Figure 4. Screenshot of the GUI developed to compute the LQG matrices sent to the RTC.

The figure (4) is a screenshot of the Graphical User Interface (GUI) we have developed for this test and commissioning. We can load the circular buffer acquired previously on-sky. It automatically reconstruct the POL slopes. Then using the set of parameters we enter as input, it computes the model used to feed the LQG controller (s-AR2 or c-PEM) and we can send the matrices to the RTC. A diagnostic button has been developed as well in order to check the performance on replay-mode using the POL slopes as perturbation. This is the GUI we will use during the on-sky testing at the end of the semester 2016B.

5. CONCLUSION

In this paper we have shown the recent developments done on the LQG TT controller framework. Simulations have shown that we can get a clear improvement in term of performance using a smarter controller (here based on LQG) than a classical integrator control law. Especially when vibrations are affecting the system, it is clear that we can use this type of controller to reject them and increase the performance of the system. A specific GUI has been developed to be ready for on-sky testing this semester. Several models can be tested, the s-AR2 or the c-PEM. They both delivered in simulations great performance. The schedule for on-sky testing is for the end of the semester 2016B.

6. ACKNOWLEDGMENTS

Based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States of America), The National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), Ministério de Ciência, Tecnologia e Inovação (Brazil) and Ministerio de Ciencia, Tecnologia e Innovación Productiva (Argentina).

REFERENCES

[1] Meimon, S., Petit, C., Fusco, T., and Kulcsár, C., "Tip tilt disturbance model identification for kalman-based control scheme: application to xao and elt systems," *J. Opt. Soc. Am. A* **27**(11), 122–132 (2010).

[2] Sivo, G., Kulcsár, C., Conan, J.-M., Raynaud, H.-F., Gendron, É., Basden, A., Vidal, F., Morris, T., Meimon, S., Petit, C., Gratadour, D., Martin, O., Hubert, Z., Sevin, A., Perret, D., Chemla, F., Rousset, G., Dipper, N., Talbot, G., Younger, E., Myers, R., Henry, D., Todd, S., Atkinson, D., Dickson, C., and Longmore, A., "First on-sky SCAO validation of full LQG control with vibration mitigation on the CANARY pathfinder," *Optics Express* **22**, 23565 (Sept. 2014).

[3] Petit, C., Sauvage, J.-F., Fusco, T., Sevin, A., Suarez, M., Costille, A., Vigan, A., Soenke, C., Perret, D., Rochat, S., Barrufolo, A., Salasnich, B., Beuzit, J.-L., Dohlen, K., Mouillet, D., Puget, P., Wildi, F., Kasper, M., Conan, J.-M., Kulcsár, C., and Raynaud, H.-F., "SPHERE eXtreme AO control scheme: final performance assessment and on sky validation of the first auto-tuned LQG based operational system," in [*Adaptive Optics Systems IV*], *Proc. SPIE* **9148**, 91480O (Aug. 2014).

[4] Kulcsár, C., Massioni, P., Sivo, G., and Raynaud, H.-F. G., "Vibration mitigation in adaptive optics control," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], **8447** (July 2012).

[5] Juvénal, R., Kulcsár, C., Raynaud, H.-F., Conan, J.-M., Petit, C., Leboulleux, L., Sivo, G., and Garrel, V., "Tip-tilt modelling and control for GeMS: a performance comparison of identification techniques," in [*Forth International Conference on Adaptive Optics for Extremely Large Telescopes.*], (2015).

[6] Crampton, D. and Ellerbroek, B., "Design and development of TMT," in [*The Scientific Requirements for Extremely Large Telescopes*], Whitelock, P., Dennefeld, M., and Leibundgut, B., eds., *IAU Symposium* **232**, 410–419 (2006).

[7] Hubin, N., Ellerbroek, B. L., Arsenault, R., Clare, R. M., Dekany, R., Gilles, L., Kasper, M., Herriot, G., Le Louarn, M., Marchetti, E., Oberti, S., Stoesz, J., Veran, J. P., and Vérinaud, C., "Adaptive optics for Extremely Large Telescopes," in [*The Scientific Requirements for Extremely Large Telescopes*], Whitelock, P., Dennefeld, M., and Leibundgut, B., eds., *IAU Symposium* **232**, 60–85 (2006).

[8] Johns, M. W., "Giant Magellan Telescope (GMT)," in [*Second Backaskog Workshop on Extremely Large Telescopes*], Ardeberg, A. L. and Andersen, T., eds., *Proc. SPIE* **5382**, 85–94 (July 2004).

[9] Milton, N. M., Lloyd-Hart, M., Baranec, C., Stalcup, Jr., T., Powell, K., McCarthy, D., Kulesa, C., and Hege, K., "Commissioning the MMT ground-layer and laser tomography adaptive optics systems," in [*SPIE Conference*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7015** (July 2008).

[10] Rigaut, F., "Ground-conjugate wide field adaptive optics for the elts," in [*Beyond Conventional Adaptive Optics*], Ragazzoni, R. and Esposito, S., eds., Astronomical Observatory of Padova (2001).

[11] Hammer, F., Sayède, F., Gendron, E., Fusco, T., Burgarella, D., Cayatte, V., Conan, J.-M., Courbin, F., Flores, H., Guinouard, I., Jocou, L., Lançon, A., Monnet, G., Mouhcine, M., Rigaud, F., Rouan, D., Rousset, G., Buat, V., and Zamkotsian, F., "The FALCON Concept: Multi-Object Spectroscopy Combined with MCAO in Near-IR," in [*Scientific Drivers for ESO Future VLT/VLTI Instrumentation*], Bergeron, J. and Monnet, G., eds., 139 (2002).

[12] Dicke, R. H., "Phase-contrast detection of telescope seeing and their correction," *Astron. Journal* **198**(4), 605–615 (1975).

[13] Rigaut, F., Neichel, B., Boccas, M., d'Orgeville, C., Vidal, F., van Dam, M. A., Arriagada, G., Fesquet, V., Galvez, R. L., Gausachs, G., Cavedoni, C., Ebbers, A. W., Karewicz, S., James, E., Lührs, J., Montes, V., Perez, G., Rambold, W. N., Rojas, R., Walker, S., Bec, M., Trancho, G., Sheehan, M., Irarrazaval, B., Boyer, C., Ellerbroek, B. L., Flicker, R., Gratadour, D., Garcia-Rissmann, A., and Daruich, F., "Gemini multiconjugate adaptive optics system review - I. Design, trade-offs and integration," *MNRAS* **437**, 2361–2375 (Jan. 2014).

[14] Neichel, B., Rigaut, F., Vidal, F., van Dam, M. A., Garrel, V., Carrasco, E. R., Pessev, P., Winge, C., Boccas, M., d'Orgeville, C., Arriagada, G., Serio, A., Fesquet, V., Rambold, W. N., Lührs, J., Moreno, C., Gausachs, G., Galvez, R. L., Montes, V., Vucina, T. B., Marin, E., Urrutia, C., Lopez, A., Diggs, S. J., Marchant, C., Ebbers, A. W., Trujillo, C., Bec, M., Trancho, G., McGregor, P., Young, P. J., Colazo, F., and Edwards, M. L., "Gemini multiconjugate adaptive optics system review - II. Commissioning, operation and overall performance," *MNRAS* **440**, 1002–1019 (May 2014).

[15] Poyneer, L. A., Palmer, D. W., Macintosh, B., Savransky, D., Sadakuni, N., Thomas, S., Véran, J.-P., Follette, K. B., Greenbaum, A. Z., Mark Ammons, S., Bailey, V. P., Bauman, B., Cardwell, A., Dillon, D., Gavel, D., Hartung, M., Hibon, P., Perrin, M. D., Rantakyrö, F. T., Sivaramakrishnan, A., and Wang, J. J., "Performance of the Gemini Planet Imager's adaptive optics system," *Applied Optics* **55**, 323 (Jan. 2016).

[16] Leboulleux, L., Sivo, G., Juvénal, R., Kulcsár, C., Garrel, V., Raynaud, H.-F., Conan, J.-M., Petit, C., Rambold, W., Gigoux, P., Marin, E., Montes, V., Moreno, C., and Trujillo, C., "Analysis of GeMS tip-tilt on-sky data: LQG implementation for vibration rejections," in [*Forth International Conference on Adaptive Optics for Extremely Large Telescopes.*], (2015).

[17] Garrel, V., Sivo, G., Marin, E., Carrasco, R., Montes, V., Lazo, M., Gigoux, P., Moreno, C., Trujillo, C., Donahue, J., van Dam, M., Rigaut, F., d'Orgeville, C., Kulcsár, C., Juvénal, R., Araujo, C., Ammons, M., and Neichel, B., "Reshaping and polishing the GeMS MCAO system," in [*Adaptive Optics Systems V*], *Proc. SPIE* (2016).

[18] Sivo, G., *Validation ciel d'une commande haute performance en optique adaptive classique et multi-objet sur le démonstrateur CANARY*, PhD thesis, Université Paris 13 (2013).

[19] Sivo, G., Raynaud, H.-F., Conan, J.-M., Kulcsár, C., Gendron, E., Vidal, F., and Basden, A. G., "Lqg control performance with the canary moao pathfinder. laboratory results and on-sky tests plan," in [*Adaptive Optics Systems III*], Proc. SPIE(2012).

[20] Sivo, G., Kulcsár, C., Conan, J.-M., Raynaud, H.-F., Gendron, E., Basden, A., Vidal, F., Morris, T., Meimon, S., Petit, C., Gratadour, D., Martin, O., Hubert, Z., Sevin, A., Chemla, F., Rousset, G., Dipper, N., Talbot, G., Younger, E., and Myers, R., "First on-sky validation of full LQG control with vibration mitigation on the CANARY MOAO pathfinder," in [*Third International Conference on Adaptive Optics for Extremely Large Telescopes (AO4ELT3).*], (May 2013).

[21] Kulcsár, C., Raynaud, H.-F., Petit, C., Conan, J.-M., and Viaris de Lesegno, P., "Optimal control, observers and integrators in adaptive optics," *Optics Express* **14**(17), 7464–7476 (2006).

[22] Petit, C., *Etude de la commande optimale en Optique Adaptative et Optique Adaptative MultiConjugue, validation numrique et exprimentale*, PhD thesis, Universit Paris 13 (2006). http://tel.archives-ouvertes.fr/tel-00134154/en.

[23] Petit, C., Fusco, T., Charton, J., Mouillet, D., Rabou, P., Buey, T., Rousset, G., Sauvage, J.-F., Baudoz, P., Gigan, P., Kasper, M., Fedrigo, E., Hubin, N., Feautrier, P., Beuzit, J.-L., and Puget, P., "The SPHERE XAO system: design and performance," in [*Adaptive Optics Systems*], *Proc. SPIE* **7015**, 70151U (July 2008).

[24] Sivo, G., Kulcsár, C., Conan, J.-M., Raynaud, H.-F., É., G., and Vidal, F., "MOAO real-time LQG implementation on CANARY," in [*Second International Conference on Adaptive Optics for Extremely Large Telescopes*], (Sept. 2011).

[25] Petit, C., Conan, J.-M., Kulcsár, C., Raynaud, H.-F., Fusco, T., Montri, J., and Rabaud, D., "First laboratory demonstration of closed-loop kalman based optimal control for vibration filtering and simplified mcao," in [*Advances in Adaptive Optics II*], **6272**, 62721T, Proc. SPIE(2006).

[26] Petit, C., Conan, J.-M., Kulcsár, C., Raynaud, H.-F., and Fusco, T., "First laboratory validation of vibration filtering with LQG control law for Adaptive Optics," *Optics Express* **16**(1), 87–97 (2008).