1st AO4ELT conference, 07008 (2010)
DOI:10.1051/ao4elt/201007008

Toward an optimal control for wide field of view AO on ELT

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Abstract. We demonstrated the faisability of full end-to-end simulations for classical and wide field of view AO on an ELT. We show simulation results for a classical Adaptive optics systems using a standard biprocessor and octoprocessor computers with a standard control algorithm and we present the performances for a telescope varying from 8 to 42 m. We propose for optimising the performance of wide field of view system to use an optimal control approach based on the FRIM algorithm.

1 Introduction

The definition of a control algorithm for a wide field of view AO system (GLAO, MCAO, MOAO, etc) is in itself a difficult problem and a question which is not totally solved. When the AO system is designed to work on an ELT, the problem becomes even trickier. In fact the very large number of degrees of freedom makes hard or impossible to use standard methods of tomography [1]. Besides that, it is impossible to think in terms of scaling laws to predict AO performances for ELTs because the atmospheric parameters are not scaled. For those reasons, and for the next generation of extremely large telescopes ELTs, we have to define, optimise and simulate tomographic control algorithms that fit with such a number of degrees of freedom. We show simulation results of a Ground Layer Adaptive Optics system with standard control algorithm and its expected performance for telescope varying from 8 to 42 m. We explore theoretical developments to define an optimized control law for an ELT.

2 Numerical simulation of an ELT with CAOS

The CAOS "system" (Code for Adaptive Optics Systems) is properly said a Problem Solving Environment (PSE) [2]. It is essentially composed of a graphical programming interface (the CAOS Application Builder) which can load different packages (set of modules)(See figure 1).MAOS (that stands for Multiconjugate Adaptive Optics Simulations) developped for multi-reference multiconjugate AO studies purpose. PAOLAC which is a simple CAOS interface for the analytic IDL code PAOLA.[3] .

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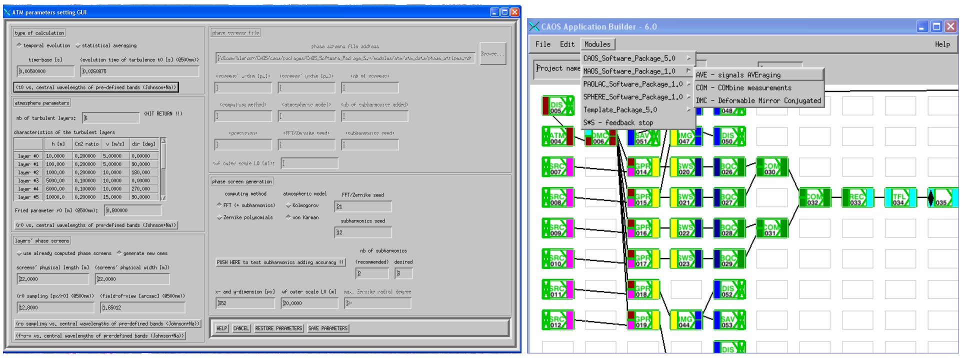

Fig. 1. Left:ATM parameters setting;Right:CAOS application builder for a Ground layer Adaptive Optics

2.1 First step

The first step of our work consisted in validating the computing capabilities for ELT simulations. First of all, using a standard biprocessor computer, we simulated classical adaptive optics with CAOS for different telescope diameters, from 8m to 28m. For larger telescopes, the biprocessor computer was not able to make the simulation.(See figure 2).

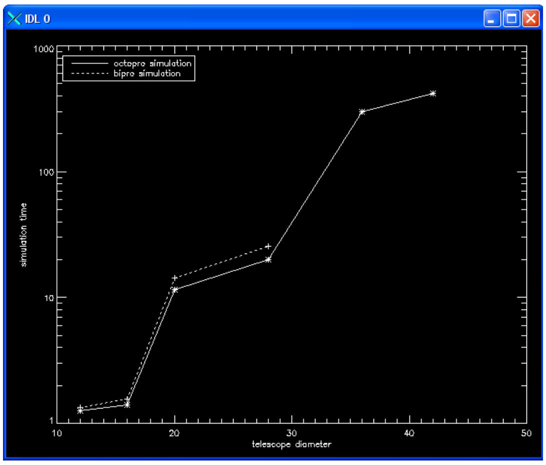

Fig. 2. The simulation time for the different simulation reached by a biprocessor and octoprocessor for a 42m

2.2 Second step

Our second step consisted in simulating classical adaptive optics on an octoprocessor computer so that we reached a 42m telescope . We present the simulation time for the different simulation reached by a bi and octoprocessor. For a 42m, 7 hours of simulation are required.(See figure 2). Even if it is a large amount of time, for an end to end simulation, it remains reasonable. Furthermore, it is interesting to notice that it is the computation of large turbulent screens that takes more time, which is the same for classical AO and wide field of view AO. This computer time estimation remains then consistent for wide field AO.

2.3 Third step

Our third step of simulation was for Ground Layer Adaptive Optics using the package MAOS. We simulated a 28m telescope on an octoprocessor, using 4 guide stars on the border of a 40 arcmin field of view. The deformable mirror is 31 * 31 actuators and the shack-hartmann WFS is 30* 30 sub-apertures. The atmosphere is composed of 4 turbulent layers at 10, 100, 1000 and 5000 m of altitude. The observed performance is particularly flat (between 30 and 35%of Strehl) on the 40arcmin field of view.(See figure 3)

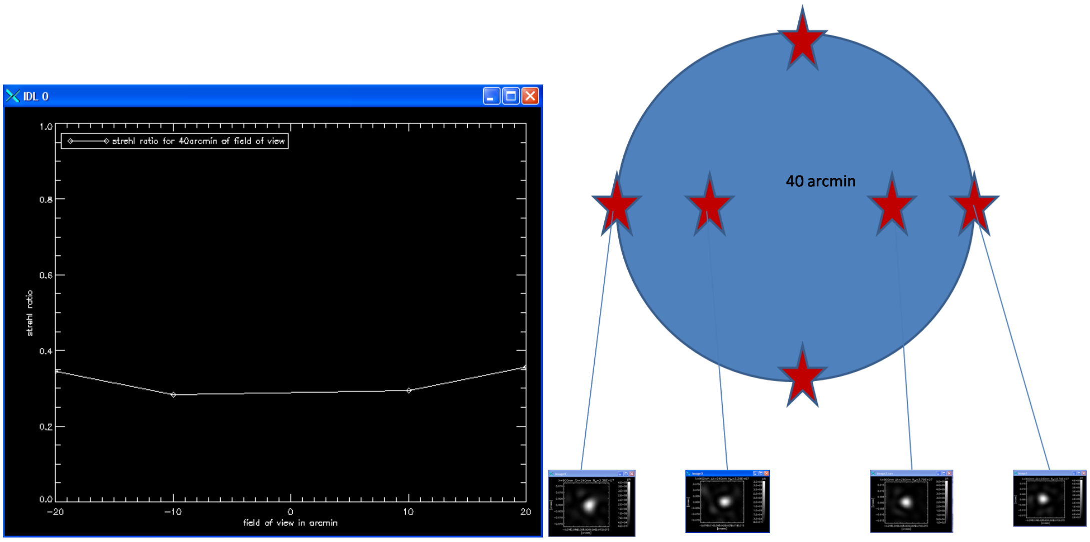

Fig. 3. Left:Strehl Ratio for a 40arcmin fielf of view; Right:Four Guide Stars on the border of a 40 arcmin field of view.

3 Optimal control algorithm for wide field of view

3.1 KALMAN

The Kalman filter is an observer with optimum gain, defined by the minimum of the estimation error variance [4]. In other word it's a recursive estimator obtained in two steps: the first step is the update, consisting in the estimation of $X_{t/t}$ using the estimated $X_{t/t-1}$ and the measurements Y_t.

$$\hat{X}_{t/t} = \hat{X}_{t/t-1} + C_{t/t-1}A_3^T(A_3C_{t/t-1}A_3^T + C_\omega)^{-1}\tilde{Y}_{t/t-1} \quad (1)$$

$$= \hat{X}_{t/t-1} + H_t\tilde{Y}_{t/t-1} \quad (2)$$

$$C_{t/t} = C_{t/t-1} - C_{t/t-1}A_3^T(A_3C_{t/t-1}A_3^T + C_\omega) \quad (3)$$

The second step is the prediction of the estimation of $X_{t+1/t}$. where $X_{t/t-1}$ is the estimation of X_t using $X_0 \cdots X_t - 1$.

$$\hat{X}_{t+1/t} = A_1\hat{X}_{t/t} + A_2u_t \quad (4)$$

$$= A_1\hat{X}_{t/t-1} + A_2u_t + A_1H_t\tilde{Y}_{t/t-1} \quad (5)$$

$$= A_1\hat{X}_{t/t-1} + A_2u_t + A_1H_t(Y_t - \hat{Y}_{t/t-1}) \quad (6)$$

In each iteration the observer compares the measurement with the estimated one given by the linear state space model and with the estimated state of the system given at the previous instant. The optimal gain is variable and its calculus requires an iterative resolution of the Ricatti's equation.

3.1.1 Optimal control law for multiconjugate adaptive optics

It is possible for wide field AO, to propose an approach based on a state-space model formalism, a Kalman filter and a feedback control derived from the classical linear estimation theory.

The choice of the state vector is crucial, vector X must contain all the variables needed for the estimation of the voltage u. For a first order AR prior-model, the state vector is then:

$$X_n = \begin{pmatrix} \phi^{tur}_{n+1} \\ \phi^{tur}_{n} \\ \phi^{tur}_{n-1} \\ u_{n-1} \\ u_{n-2} \end{pmatrix}$$

And the state model is:

$$X_{n+1} = \begin{pmatrix} A & 0 & 0 & 0 & 0 \\ Id & 0 & 0 & 0 & 0 \\ 0 & Id & 0 & 0 & 0 \\ 0 & 0 & 0 & Id & 0 \end{pmatrix} X_n + \begin{pmatrix} 0 \\ 0 \\ 0 \\ Id \\ 0 \end{pmatrix} u_n + \begin{pmatrix} \nu_n \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$Y_n = D\begin{pmatrix} 0 & 0 & M^L_\beta & 0 & M^{DM}_\beta N \end{pmatrix} X_n + w_n$$

By proceeding as above we can estimate the turbulent phase at the instant t+1. So the voltages is then given by:

$$u_n = P_{[\alpha;DM]}\hat{\phi}^{tur}_{n+1/n}$$

We should note that α and β are the directions of interest objects and WFS respectively.

3.2 FRIM: FRactal Iterative Method

For extremely large telescopes (ELT's) the number of actuators will be in the range $10^4 - 10^5$, or computing the control matrix using standard method scales as $O(N^3)$.Thus, more efficient algorithms are required. A minimum variance iterative algorithm for fast wavefront reconstruction and fast control of an adaptive optics system was developed by Tallon et al [5]. It is based on an iterative method to compute the unknowns by using direct measurement, so no need to store a precomputed full inverse matrix , unless the main problem with this iterative methods is the increase of the number of iteration with number of unknown [6, 7]. Preconditioners are thus required to achieve a small number of iterations and to speed up the iterative algorithm. FRIM makes use of a fractal operator K based on a generalization of the mid-point algorithm of Lane et al [8] to generate a Kolmogorov phase screen, this fractal operator is not sparce but is implemented so that it requires $O(N) \approx 6N$ operations.

3.2.1 Minimum variance solution

The best reconstruction matrix R or the minimum variance reconstructor is given by the following equation [9]:

$$R\dagger = (S^T \cdot C_n^{-1} \cdot +C_w^{-1})^{-1} \cdot S^T \cdot C_n^{-1}$$

3.2.2 Iterative method

Since R requires the inversion of $N \cdot N$ matrix and the storage of $R \cdot d$ require $4N^2$, we have to use an iterative method to solve the linear equation: $A \cdot x = b$, where C_w is the a priori covariance matrix of the wavefront. Furthermore, computing the regularization term requires the introduction of a new term u so that: $w = K \cdot u$ and which covariance matrix is the identity.

3.2.3 Preconditioner

Using the fractal operator as a preconditioner reduces the number of iterations in the range of 5-10 whatever is the size of the adaptive optics system.

3.3 Conclusion

With a Kalman filter the operations needed at each step to compute the new phase estimate are given by the three components:

$$\begin{pmatrix} \phi_{n+2/n} \\ \phi_{n+1/n} \\ \phi_{n/n} \end{pmatrix} = M_1 \begin{pmatrix} \phi_{n+1/n-1} \\ \phi_{n/n-1} \\ \phi_{n-1/n-1} \end{pmatrix} + M_2(Y_n^{meas} - M_3 \cdot u_{n-2})$$

And the new commands given by:

$$u_n = M_4\hat{\phi}_{n+1/n}$$

where computing M_2 , M_3, M_4 and H_n follows $O(N^2)$.

Introducing a Frim-like method in the computation of these matrix would decrease the number of operations which is especially crucial for the ELTs where the number degrees of freedom will be in the range $10^4 - 10^5$.

4 Conclusion

We demonstrated the faisability of full end-to-end simulations for classical and wide field of view AO on an ELT. This demonstration was based on a simple GLAO system using a basic integrator control law. We propose for optimising the performance of wide field systems to use an optimal control approach based on the FRIM algorithm.

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