Evolving the METIS soft real-time control system out of the simulation environment

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ABSTRACT

METIS, the Mid-Infrared ELT Imager and Spectrograph is a first-generation ELT instrument scheduled to see first light in 2029. Its two main science modules are supported by an adaptive optics system featuring a pyramid sensor with 90x90 sub-apertures working in H- and K-band. The wavefront control concept for METIS' single-conjugate adaptive optics relies on a synthetic calibration that uses a model of the telescope and instrument to generate the interaction and control matrices, as well as the final projection on a modal command vector. This concept is enforced owing to the absence of a calibration source in front of the ELT's main deformable mirror. The core of the synthetic calibration functionality is the Command Matrix Optimiser module, which consists of several components providing models for various parts and aspects of the instrument, as well as the entire reconstructor. Many are present in the simulation environment used during the design phases, but need to be re-written and/or adapted for real-life use. In this paper, we present the design of the full command matrix optimisation module, the status of these efforts and the overall final concept of METIS' soft real-time system.

Keywords: Adaptive Optics, Real-Time Computing, Calibration, Wavefront Control

1. INTRODUCTION

The 39 m Extremely Large Telescope (ELT) of the European Southern Observatory (ESO) currently under construction on Cerro Armazones in Chile features an integrated deformable mirror M4 and tip-tilt mirror M5 for Adaptive Optics (AO) operations. While an intermediate f/4.4 focus is available between the entrance pupil, co-located with M1, and these adaptive mirrors, the optical quality at this focal point is bad and the location, in the middle of the central hole in M4, is difficult to access. It is thus not foreseen to operate ELT AO systems with a classical calibration source [1]. Calibration for the first generation instruments, among them METIS, is thus foreseen to happen in a pseudo-synthetic way, without actually seeing the adaptive mirrors.

The pseudo-synthetic calibration foreseen for the Single-Conjugate AO (SCAO) system of METIS relies on a detailed model of the critical components of the AO system, the entrance pupil and the adaptive mirror M4 and their respective locations and orientations in space, the pyramidal prism and the detector of the Pyramid Wave Front Sensor (P-WFS) and again their location and orientation in space, and the P-WFS's modulation system. This model is inherently similar to the one used for simulation during the design phases of the instrument.

In particular, also during the design phase a calibration procedure was used that involved the derivation of the critical interaction and command matrices and the critical intermediate projection step by taking into account the parameters of the components mentioned above. The main difference between the two systems is

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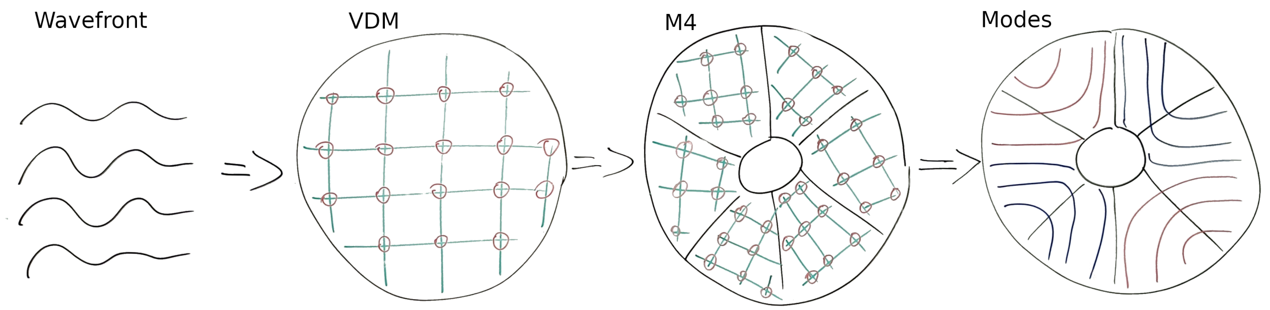


Figure 1. Spatial wavefront reconstruction steps: the wavefront is reconstructed on a virtual deformable mirror (VDM) actuator grid, projected onto M4 actuator space and finally onto a modal command vector.

that simulations were done in the COMPASS environment [2], while the productive system implemented on METIS' Soft Real-Time Computer (SRTC) is being developed in the framework of the ESO RTC Toolkit*. The standards to adhere to, and the non-open source nature of the COMPASS package inhibit its direct use in METIS' AO control system. In addition, we need a fast implementation, as parts of the command matrix will have to be updated dynamically at rates of up to 0.5 Hz.

This paper describes the Command Matrix Optimiser (CMO), the core SRTC component responsible for deriving the, who would have thought, Command Matrix (CM) of the SCAO system, and which contains all the modeled components mentioned beforehand.

2. METIS WAVEFRONT CONTROL STRATEGY

The wavefront control strategy of METIS consists of the following four steps and is discussed in more detail in [3]:

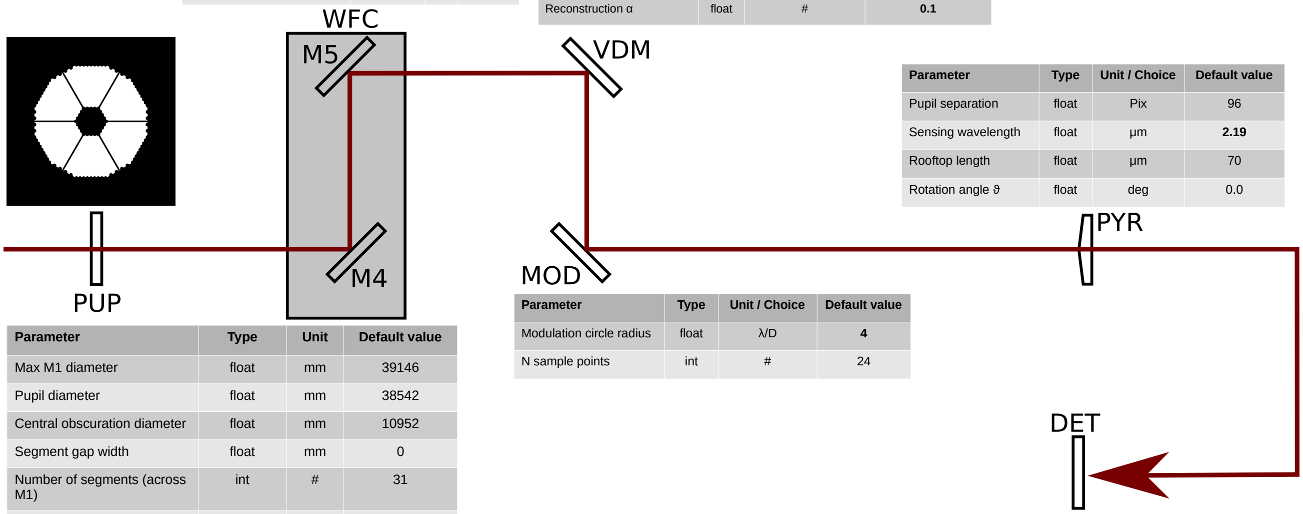
1. Tikhonov-regularised spatial wavefront estimation/reconstruction on a zonal Cartesian coordinate system tied to the P-WFS sampling pixel grid,
2. the regularised projection onto a control space defined by the M4 actuator geometry including correction of mis-registrations and rotation between the P-WFS coordinate grid and the ELTs M4/M5,
3. the projection onto a global modal control space, which also is used to communicate with the Central Command System (CCS) of the ELT, and
4. the time-filtering through the application of proportional-integral control before sending the modal command vector to the ELT's CCS.
5. CCS will internally convert to actuator commands readied for the ELTs collaborative tip-tilt (TT) offloading scheme whilst avoiding hitting the mirror constraints in amplitude, speed and force. This last step happens outside of the METIS real-time system.

The first three steps represent the spatial reconstruction of the wavefront, which are being combined in the command matrix, while the fourth step is done separately, and the fifth happens outside of METIS' RTC. This separation into spatial and temporal control is also reflected in the design of the METIS Hard Real-Time Computer (HRTC) [4]. Figure 1 sketches an overview of the spatial reconstruction. The command matrix C can be expressed as a product of three matrices:

$$C = MPR$$

with R being the reconstruction matrix that reconstructs the wavefront in the virtual actuator space of a Virtual Deformable Mirror (VDM) from the Wavefront Sensor (WFS) measurements (step 1 above), P being

*ESO RTC Toolkit: https://www.eso.org/∼eltmgr/RTCTK/documents/v2.0.0/sphinx_doc/html/index.html



Parameter	Type	Unit	Default value
Influence functions	float [5352x64x64]	μ m	
Influence function positions	float [5352x2x1]	mm	
Modes to command matrix (**m2c**)	float [5352 x 4866]	nm	
Screen size	int	pix	736
Projection α	float	#	**0.1**
Rotation angle	float	deg	**0.0**
Shift	float [2x1]	mm	**[0.0,0.0]**
Scaling factor	float	#	**1.0**

Parameter	Type	Unit / Choice	Default value
Influence function type	string	["rigaut" / "pyramid"]	"pyr"
Calibration poke amplitude	float	nm	50
Actuator coupling	float	#	0.0
Valid actuator threshold	float	#	**0.03**
Reconstruction α	float	#	**0.1**

Parameter	Type	Unit / Choice	Default value
Pupil separation	float	Pix	96
Sensing wavelength	float	μm	**2.19**
Rooftop length	float	μm	70
Rotation angle ϑ	float	deg	0.0

Parameter	Type	Unit / Choice	Default value
Modulation circle radius	float	λ/D	**4**
N sample points	int	#	24

Parameter	Type	Unit	Default value
Max M1 diameter	float	mm	39146
Pupil diameter	float	mm	38542
Central obscuration diameter	float	mm	10952
Segment gap width	float	mm	0
Number of segments (across M1)	int	#	31
Spider arm width	float	mm	540
Oversampling factor (for generation)	int	#	8
Target array size	int	pix	2048
Rotation angle	float	deg	**0**
Shift	[float, float]	mm	**[0,0]**
Pixel scale	float	m/pix	0.055556

Parameter	Type	Unit / Choice	Default value
Pixel scale	float	m/pix	0.44
use_global_norm	bool	#	True
valid_fracillum	float	#	**0.01**

Figure 2. Components modeled in the CMO and the parameters kept open for configuration. Parameters with a bold-face default value are expected to change dynamically and require re-generation of a CM when doing so.

the projection matrix projecting from VDM actuator space to M4 actuator space (step 2), and finally M being the matrix to project from M4 actuator space onto the global modal control space (step 3).

In order to calibrate the command matrix on the SRTC (see [5]) a number of actual hardware components and a virtual mirror need to be modeled. These are described in the following section. Based on these models, the elements of the command matrix need to be calculated in several software components we call optimisers. We give a description of these in Section 4.

3. SYSTEM COMPONENTS

To produce a valid calibration for METIS SCAO, the CMO contains a forward model of the instrument through which an optical propagation is calculated every time the response of the system needs to be calibrated. Some, but not all of these components have a correspondence in the real instrument hardware, and all have a number of parameters kept for possible configuration during the operation of the instrument as they are expected to change on timescales shorter than the lifetime of the instrument. Figure 2 gives an overview of the components and the principal parameters which are described in more detail here:

3.1 PUP

The telescope pupil (PUP) is modeled by an amplitude mask representing the shape of the entrance pupil. A pupil server produces these shapes and publishes them to the rest of the CMO for CM generation. The parameters used for configuration are essentially:

Mirror geometry Inner and outer diameter of the pupil itself, and the actual maximum diameter of M1 along with the number of hexagonal segments covering this diameter for the generation of the pupil shape itself. In addition, the width of the spider arms is adjustable. Following results of an extensive analysis, it is not foreseen to take individual missing segments or reflectivity errors into account. An initially different mirror shape due to several rings of segments not being present during early operations will demand an adaptation, though.

Array generation The array that eventually holds the pupil mask is down-sampled from a larger array, the factor between the two sizes being controlled by an oversampling factor. This is to reduce aliasing caused by having only fully transparent or fully opaque pixels in the mask. The downsampling produces grey values in between.

Registration While motion of the pupil w.r.t. the WFS is compensated by a dedicated pupil position mirror, monitor, and control loop, the pupil will still rotate during observations. We will adapt our CM according to the relevant orientation at all times, thus generated pupil masks have configurable parameters for location (likely not needed as mentioned before), rotation, and scale.

3.2 WFC

The Wavefront Corrector (WFC) device in the forward model essentially represents a combination of the adaptive mirrors M4 and M5. In order to adapt to operation during Assembly, Integration, and Testing (AIT), and possibly on different telescopes, we keep the description of the WFC characteristics open. These are characterised by the following parameters:

Influence functions The influence functions (IFs) of the high-order Deformable Mirror (DM) are given by a square array containing the Optical Path Difference (OPD) of each IF at any given array pixel, and the location at which the IF must be placed on the WFC.

Modes to command matrix (m2c) At the ELT, METIS SCAO requests wavefront shapes from the control system that will then be put on the wavefront correction devices. The request is made in form of a modal command vector containing coefficients, each of which representing one mode from the chosen basis. The relation between the modal vector and the actual commands applied to the mirror is the m2c-matrix. We essentially need its inverse, c2m, for the regularised projection of the reconstructed wavefront onto the modal command vector.

Projection α Regularisation factor for the projection of the reconstructed wavefront onto the modal basis.

Registration Like the pupil, M4 and thus its (and consequently WFC's) actuators can move with respect to the WFS during observation. Note that its motion is independent of that of the pupil itself. We thus again have the location, scale and rotation parameters. Note that the application of these parameters does actually not happen in the WFC module, but in the Projection Matrix Optimiser as described in Sec. 4.4

3.3 VDM

The virtual deformable mirror is, as its name implies, not really a hardware device. Yet, it is a component in the forward model used as a deformable mirror during our zonal calibration procedure. Its actuator positions are aligned to the grid defined by the detector of the WFS. It is characterised by the following parameters:

Influence function (IF) type and coupling being a virtual mirror, we can have any IF shape we deem suitable. The default is to move bi-linear functions ("pyramids") with zero coupling between them.

Calibration poke amplitude The amplitude that each actuator is poked with during the calibration procedure.

Valid actuator threshold A threshold calculated on the relative response of the WFS to each actuator poke w.r.t. the maximum response, below which an actuator on the VDM is discarded.

Reconstruction α Regularisation factor for the MMSE inversion of the recorded interaction matrix.

3.4 MOD

The modulator (MOD) is approximated in the digital model by adding WFS images taken at different positions on the modulation circle. Parameters are the radius of the modulation circle, and the number of points at which WFS response images are calculated.

3.5 PYR

The pyramid prism (PYR) is represented by a pyramid-shaped phase screen. The physical glass pyramid is extremely well characterised, its angles and roof length being known to better than $5''$ or 1μm. The corresponding surface angles on the numerical phase screen will be calculated from:

Pupil separation The resulting separation of the pupils on the detector grid, and

Rooftop length The known rooftop length.

Sensing wavelength It is the central parameter of the forward model.

Rotation angle During assembly, the pyramid might slightly be rotated with respect to the other components, in particular the detector. We can adapt any such eventuality by means of rotating the numerical model correspondingly.

3.6 DET

The detector pixels are effectively the sub-apertures of our wavefront sensor. The parameters defining these are:

Pixel scale The effective size of the sub-apertures when projected onto the pupil is equivalent to the effective size of one detector pixel, the metres per pixel thus determine the sampling of our sensor.

Global norm The slope computation of the pyramid sensor applies a normalisation to the intensity, this can be done globally as an average across all sub-apertures, or locally on each sub-aperture individually.

Valid subapertures If a sub-aperture is used or not depends on the flux it receives. Sub-apertures that receive less than a certain fraction of the maximum flux are discarded.

4. COMMAND MATRIX OPTIMISATION

Figure 3 gives an overview over the software components that make up the Command Matrix Optimiser and their inter-dependencies. Some components model real (or virtual) hardware, while the Modes Server provides the externally computed global modes definition. The WFS Signal Computation replicates the way the WFS signal is computed from the WFS images on the HRTC. The task of the optimisers, which are described in more detail in this section, is to produce data products that finally make up the command matrix that is in charge of the spatial part of the wavefront reconstruction.

The computation of these data products is triggered by a request containing parameters which are described in Section 3 and Figure 2. Each optimiser object is implemented with an internal logic, that decides if its assigned data product needs to be updated, and if so, if a previously computed version can be used or whether an on-the-fly re-computation needs to be done.

As an example, the computation of the interaction matrix is computationally expensive and takes a relatively long time, while it depends only on a relatively small number of dynamically changing parameters. It is thus a data product that can easily be pre-computed: the VDM is bound by definition to the wavefront sensor grid, while the pupil position on the wavefront sensor is assumed to be very stable, since it is monitored and corrected by a pupil position control loop, so that the parameter space that influences the updates of this data product is relatively small: the most important one being the rotation of the pupil on the detector.

As a counter example, the mis-registration of the mirror M4 on the wavefront sensor detector has a much larger parameter space: on top of the rotation, it encompasses shifts in x- and y-direction, potentially magnification and other effects so that a pre-computation to cover the whole parameter space might not be feasible. Fortunately, computing the projection from these parameters takes much less computational effort (and thus time) and will be done mostly on-the fly.

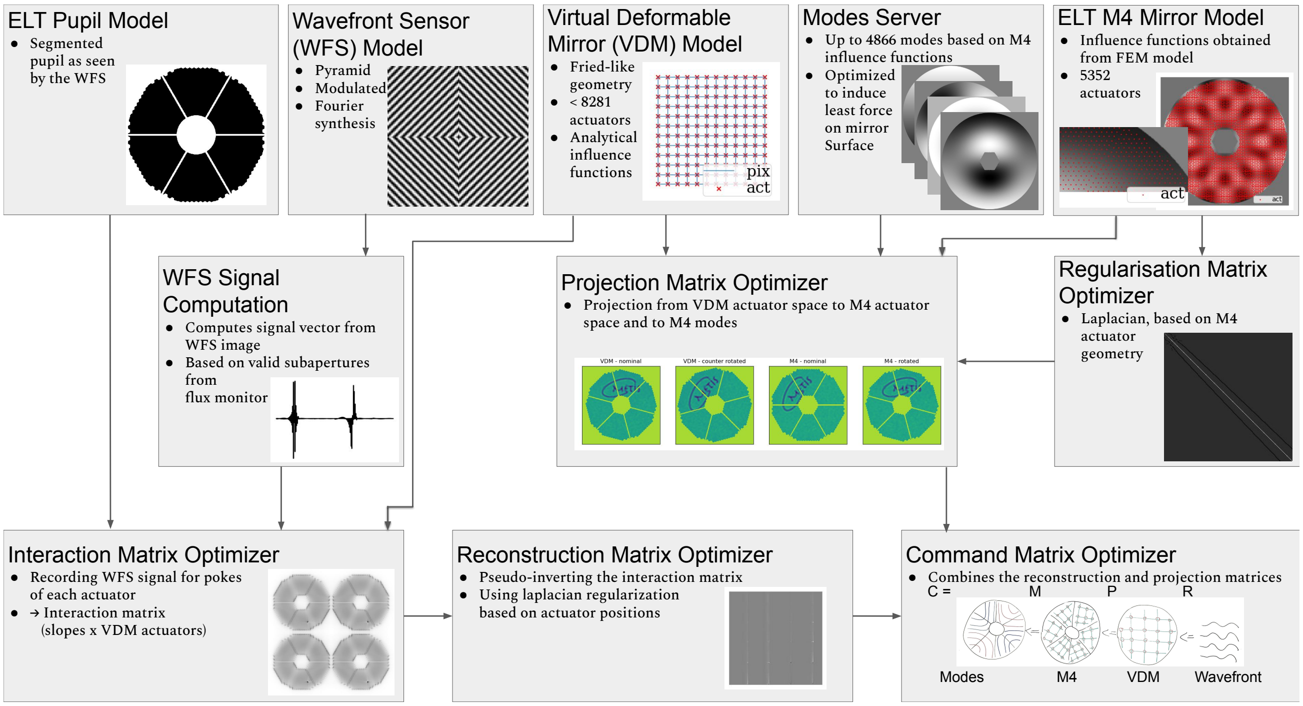


Figure 3. Overview over the elements of the Command Matrix Optimiser. Arrows indicate direction flow of data.

4.1 Command Matrix Optimiser

The task of the Command Matrix Optimiser is simply to compile the products of the Reconstruction Matrix Optimiser (RMO) and the Projection Matrix Optimiser (PMO) by computing a matrix-matrix multiplication $C = (MP)R$, where the product MP has already been computed by the PMO. In the worst case, when the target moves close to zenith and the telescope needs to rotate fast around its vertical axis, we assume that the command matrix need to be updated every 2s.

4.2 Interaction Matrix Optimiser

The task of the Interaction Matrix Optimiser is to compile the interaction matrix I. To this end, each actuator of the VDM is poked, before being evaluated by the forward model of the simulated pyramid wavefront sensor. The forward model consists of a propagation onto the pyramid tip implemented as a Fourier transform to the focal plane, an application of the pyramid phase screen, and another propagation back to the pupil plane implemented by another Fourier transform. Thus two Fourier transforms are being carried out for each actuator for each modulator position, resulting in a total of about 400,000 Fourier transforms for the full calibration process. Due to this extensive use of Fourier transforms on relatively large arrays, this step is expected to be the most compute-intensive step within the command matrix calibration process.

Based on the images synthesised by the wavefront sensor model, the WFS signal is computed by correlating pixels from the four resulting pupil images within in externally provided mask of valid sub-apertures in x- and y-direction:

$$s_x = \frac{(B+D)-(A+C)}{n} - r_x$$

$$s_y = \frac{(C+D)-(A+B)}{n} - r_y$$

with A, B, C and D being values of a corresponding pixel in the four pupil images, n being a normalisation factor based on alternatively the total or local photon counts and r_x, r_y being the reference WFS signal measurements for a flat wavefront. The WFS signal for a single actuator poke then is vector $\vec{s}$ of all signals s_x and s_y for all valid sub-apertures.

The Interaction Matrix Optimiser collects these WFS signals for all VDM actuator pokes in an interaction matrix I of dimensions (#actuators $\times 2 *$ #valid sub-apertures).

Efforts to reduce the total number of actuator pokes during the calibration by identifying actuators that produce identical or very similar response vectors in the interaction matrix are under way, but as a safe fall-back the all-actuator solution remains the default for now.

4.3 Reconstruction Matrix Optimiser

The RMO computes the reconstruction matrix R as a Thikonov regularised inverse of the interaction matrix I provided by the Interaction Matrix Optimiser:

$$R = (I^T I + \alpha_{\mathrm{Rec}} {\Delta_{\mathrm{VDM}}}^2)^{-1} I^T$$

R then can be used to reconstruct the wavefront in the space of VDM actuators from a vector of wavefront sensor signals $\vec{s}$. For regularisation, a Laplacian matrix Δ_{VDM} based on the geometry of the valid actuators, i.e. the actuators that give rise to enough signal within the pupil, is used.

The interaction matrix and with it, the reconstruction matrix needs to be updated when the position or rotation of the pupil on the wavefront sensor detector changes, but thanks to splitting the approach into wavefront reconstruction and projection, not for any mis-registration of the mirror M4 with regard to the WFS.

4.4 Projection Matrix Optimiser

The PMO creates a matrix that projects from the zonal VDM actuator space onto a global modal space defined on M4 actuator influence functions. This task is divided into to two sub-tasks: first creating a projection matrix P that projects from a zonal VDM actuator space onto a zonal M4 actuator space, and second to project from the zonal M4 actuator space onto a modal basis via a matrix M which is provided by the Modes Server. The Projection Matrix Optimiser returns the product PM of these two matrices.

In order to create the matrix P consider the following. Let N_{M4} be a matrix that encodes the influence functions of M4, so that each row contains the influence of an individual actuator (a 'poke' if you will). Creating a representation of the shape S_{M4} of the surface of M4 then can be calculated by multiplying with a command vector $\vec{c}_{\mathrm{M4}}$: $S_{\mathrm{M4}} = N_{\mathrm{M4}}\vec{c}_{\mathrm{M4}}$. In an equivalent way a matrix N_{VDM} and a command vector $\vec{c}_{\mathrm{M4}}$ can be defined for the VDM, so that we can describe the shape of the surface of of the VDM by $S_{\mathrm{VDM}} = N_{\mathrm{VDM}}\vec{c}_{\mathrm{VDM}}$. Given a command vector $\vec{c}_{\mathrm{VDM}}$ which results from the wavefront reconstruction, we solve for $\vec{c}_{\mathrm{M4}}$ to arrive at a projection matrix P:

$$\begin{aligned} S_{\mathrm{M4}} &\stackrel{!}{=} S_{\mathrm{VDM}} \\ \leftrightarrow N_{\mathrm{M4}}\vec{c}_{\mathrm{M4}} &\stackrel{!}{=} N_{\mathrm{VDM}}\vec{c}_{\mathrm{VDM}} \\ \leftrightarrow \vec{c}_{\mathrm{M4}} &= \tilde{N}_{\mathrm{M4}} N_{\mathrm{VDM}}\vec{c}_{\mathrm{VDM}} \\ \leftrightarrow \vec{c}_{\mathrm{M4}} &= P\vec{c}_{\mathrm{VDM}} \end{aligned}$$

where

$$\tilde{N}_{\mathrm{M4}} := (N_{\mathrm{M4}}^T N_{\mathrm{M4}} + \alpha_{\mathrm{Proj}} {\Delta_{\mathrm{M4}}}^2)^{-1} N_{\mathrm{M4}}^T$$

The inverse of N_{M4} is calculated using a regularisation matrix based on the M4 geometry provided by the Regularisation Matrix Optimiser. For more details on the projection see [6].

The projection matrix P has to be updated during operation of the telescope whenever $M4$ moves with respect to the wavefront sensor. This happens for example in a foreseeable way during telescope operation when the pupil and M4 rotate to track a target, but also can be be triggered due to less foreseeable effects creating a mis-registration that will be monitored in a secondary control loop [7].

In practice, we can apply the inverted mis-registration to the VDM instead of applying the nominal mis-registration to M4. This allows us to pre-compute the M4 related data products, e.g. N_{M4}. The only matrix that needs to be updated on a regular basis is the sparse N_{VDM} which is quite fast to compute due the VDM's IFs being analytical functions, so that we can provide very fast CM updates during closed-loop operation.

4.5 Regularisation Matrix Optimiser

The Regularisation Matrix Optimiser creates a Laplacian matrix used for the regularisation of the inversion of N_{M4} in the computation of the projection matrix [6]. We assume this matrix won't need to change on a regular basis, as the M4 geometry is fixed (not withstanding potential damage to actuators over the lifetime of the project).

4.6 Modes Server

Modes for a given deformable mirror usually are defined through a command-to-mode ($c2m$) matrix, where each mode is specified by a set of coefficients to be multiplied with the zonal influence functions of the actuators of the mirror. Here, the Modes Server provides the system with the pseudo-inverse of this $c2m$ matrix, in this paper denominated with M. As with regularisation matrix described in Section 4.5, we assume this matrix will not change on a regular basis, as it is tied directly to the geometry of M4. We foresee to use Force-aware Karhunen-Loeve modes described in more detail in [8, 9].

5. SYSTEM IDENTIFICATION

Fig. 2 shows the parameters of the individual components in the CMO's forward model that are kept open for configuration and performance optimisation. However, only a limited number of these, namely the ones that have bold-face default values in the figure, are actually expected to change dynamically. Such dynamical changes occur either due to changing geometry when the telescope is tracking an object in the sky, or because of changing atmospheric or instrumental conditions which require an adaptation of the control parameters. Of the latter, we only have an extremely limited number, namely the two regularisation factor α_{rec} and α_{M4}, and the modulation radius of the WFS.

All other parameters are expected to either stay constant forever, or change on longer timescales, so that they can be "calibrated" either once and for all, or at regular, yet long intervals during the instrument's lifetime. Such calibrations are usually referred to as "system identification". This system identification will happen during various stages of the project. Initially during integration and test, when e.g. the properties of the pyramid prism are determined and it's position and orientation with respect to the detector are determined. Good values for the valid sub-aperture and actuator thresholds will be determined during either sub-system or system testing in the respective integration test set-ups. Final determinations of M4 IFs and refinement of the c2m matrix on the other hand are expected during on-sky commissioning.

6. SYSTEM TESTS

Testing the CMO module before commencing on-sky operations at the ELT will happen in three stages:

1. Testing in the simulation environment: In this stage, a CMO-generated command matrix will be used in the existing simulation set-up, replacing the internally generated one. The goal is a proof that all implemented functionalities work as expected and the model we developed can actually match the one that exists elsewhere, in this case in COMPASS. This test is foreseen for summer 2024.

2. Testing in the integration facility: In this stage, the SCAO module of METIS will be coupled to and illuminated by a dedicated ELT simulator. The simulator mimics the telescope pupil and contains a DM, plus various mechanisms to introduce several kinds of mis-registration. Functionality will already have been verified at this stage, but this time the goal is to prove our model cannot only match another model, but real hardware. This test is foreseen for the first quarter of 2025.

3. Testing on-sky: In this stage, we want to inject a CMO-generated command matrix into the control system of LINC-NIRVANA [10, 11] at the Large Binocular Telescope (LBT). This will require several adaptations in the forward model and is foreseen for 2025.

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REFERENCES

[1] Cayrel, M., "E-ELT optomechanics: overview," in [*Ground-based and Airborne Telescopes IV*], Stepp, L. M., Gilmozzi, R., and Hall, H. J., eds., **8444**, 84441X, International Society for Optics and Photonics, SPIE (2012).

[2] Gratadour, D., Puech, M., Vérinaud, C., Kestener, P., Gray, M., Petit, C., Brulé, J., Clénet, Y., Ferreira, F., Gendron, E., et al., "COMPASS: an efficient, scalable and versatile numerical platform for the development of ELT AO systems," in [*Adaptive Optics Systems IV*], **9148**, 2173–2180, SPIE (2014).

[3] Correia, C. M., Feldt, M., Steuer, H., Shatokhina, J., Obereder, A., Neureuther, P., Kulas, M., Coppejans, H., de Xivry, G. O., Scheithauer, S., et al., "Elt metis wavefront control strategy," in [*Adaptive Optics Systems VIII*], **12185**, 311–324, SPIE (2022).

[4] Kulas, M., Hugo, C., Steuer, H., Bertram, T., Correia, C., Philip, N., and Briegel, F., "The RTC for METIS SCAO," in [*Adaptive Optics for Extremely Large Telescopes 7th Edition*], (2023).

[5] Kulas, M., Steuer, H., Coppejans, H., Bertram, T., Briegel, F., Naranjo, V., Feldt, Markus Correia, C., Obereder, A., Absil, O., Orban de Xivry, G., and De Meester, W., "The METIS AO Control System at the beginning of MAIT," in [*Adaptive Optics Systems IX*], *Proc. SPIE* (2024).

[6] Obereder, A., Bertram, T., Correia, C., Feldt, M., Raffetseder, S., Steuer, H., and Stadler, B., "On how to gain 60nm RMS (for the instrument METIS) in AO control," in [*Adaptive Optics Systems IX*], *Proc. SPIE* (2024).

[7] Correia, C., Steuer, H., Feldt, M., Obereder, A., Kulas, M., Coppejans, H., Orban de Xivry, G., Absil, O., and Bertram, T., "Handing over from the ELT: online METIS mis-registration calibration with crazy fast control matrix updates," in [*Adaptive Optics Systems IX*], *Proc. SPIE* (2024).

[8] Verinaud, C., "Tutorial for Force-optimized Modal Basis computation," tech. rep., ESO (Nov. 2020).

[9] Correia, C. M., Feldt, M., Steuer, H., Shatokhina, J., Obereder, A., Neureuther, P., Kulas, M., Coppejans, H., Orban de Xivry, G., Scheithauer, S., and Bertram, T., "ELT METIS wavefront control strategy," *Proc. SPIE* **12185** (2022).

[10] Herbst, T., Ragazzoni, R., Andersen, D., Boehnhardt, H., Bizenberger, P., Eckart, A., Gässler, W., Rix, H.-W., Rohloff, R.-R., Salinari, P., Soci, R., Straubmeier, C., and Xu, W., "LINC-NIRVANA: a Fizeau beam combiner for the Large Binocular Telescope," in [*Interferometry for Optical Astronomy II*], Traub, W. A., ed., **4838**, 456 – 465, International Society for Optics and Photonics, SPIE (2003).

[11] Herbst, T. M., Bertram, T., Arcidiacono, C., Bergomi, M., Berwein, J., Bizenberger, P., Briegel, F., Farinato, J., Klettke, M., Marafatto, L., Mathar, R., McGurk, R., Ragazzoni, R., Santhakumari, K. K. R., and Viotto, V., "Installation and commissioning of the LINC-NIRVANA near-infrared MCAO imager on LBT," in [*Ground-based and Airborne Instrumentation for Astronomy VII*], Evans, C. J., Simard, L., and Takami, H., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10702**, 107020U (July 2018).