PhD subject

"Exoplanet imaging adaptive optics control for SPHERE+ and beyond"

Keywords

Adaptive optics simulations and experiments, model-based control, data-driven identification, stochastic linear state space models, Kalman filtering, multi-objective control, Exoplanet detection instruments

Laboratories and contacts

Collaboration between Institut d'Optique Graduate School (Palaiseau, France) and the European Southern Observatory (Garching, Germany).

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Context

One of the most exciting science goals with current ground-based very large telescopes is the direct imaging of Exoplanets. Since 2014 the SPHERE instrument [1] at ESO's Very Large Telescope (VLT) provides such a capability, achieving imaging contrasts approaching one part in a million at a few hundred milliarcseconds from the parent star. This is sufficient to detect very young giant planets at relatively large orbital separations of about 10 AU or more, as spectacularly demonstrated, e.g., by the discovery of PDS 70b in 2018 [2] .

A key technology for high-contrast imaging from the ground is Adaptive Optics (AO) which corrects for the image blurring introduced by Earth's turbulent atmosphere. AO measures the dynamic deformation of the light-wave with a wavefront sensor (WFS) at a high cadence (typically faster than 1 kHz) and controls a deformable mirror (DM) to correct for this deformation. These AO systems dedicated to high-contrast imaging are called eXtreme AO (XAO) systems.

While SPHERE and its XAO system SAXO [3] have been very successful, new technological developments in the fields of WFS and DM promise a further boost in AO correction performance which will greatly enlarge the number of Exoplanets which can directly be imaged with the instrument. The SAXO+ project [4] will add a second AO system which will further reduce the first system's (SAXO's) residuals, resulting in a 2-stage Cascade AO (CAO) system. Because it is working on residuals, the 2nd stage is able to embed the novel high-sensitivity but small linear range Pyramid wavefront sensor. The main objective of SAXO+ is to improve contrast at small angular separation. However, slowly evolving or long-life speckles in the scientific images prevent efficient exoplanet detection. Because these speckles can be partly corrected by the AO loop, the reduction of speckle lifetime also needs to be addressed.

The goal of the PhD thesis is to explore further the CAO control structure of the SAXO+ system together with predictive control strategies, in order to improve performance. Experimental results are expected to be obtained on an AO laboratory bench at ESO [5] . Extension to large degrees of freedom will also be considered. Indeed, a CAO system is envisioned for the future Planetary Camera and Spectrograph (PCS [6]) that will equip the 39 m-diameter European Extremely Large Telescope (ELT).

PhD subject description

Imaging faint exoplanets at small angular separations is a demanding science goal. In order to reach the exacting requirements, SAXO+ will be composed of two AO stages, SAXO and a new AO system, arranged in cascade. The first stage employs a DM with 41 actuators across the aperture and a Shack-Hartmann WFS with a maximum loop frequency of around

1.4 kHz. The second stage will feature a smaller resolution DM (24-32 actuators across, to be defined) and a Pyramid WFS with a loop frequency of more than 2 kHz. The control of the whole system should achieve the highest possible imaging contrast by minimizing two major terms of the XAO error budget:

- the finite temporal correction bandwidth of the XAO system, that leads to an imperfect correction of very rapid changes of the wavefront, which dominate the residual error at small angular separations [7] ;
- the chromaticity of the refractive index of air, that leads to slightly different optical wavefronts at the science wavelength (near infra-red) and the AO wavefront sensing wavelength (red optical). The difference shows up as a residual wavefront error, which is proportional to the incoming uncorrected wavefront and dominates the error budget at the smallest angular separations [8] .

These terms are impacted by the structure and components parameters of the CAO and by the control law chosen for the second stage. Additionally, reducing speckle lifetime or imposing a specific behaviour in the scientific image could be accounted for through a multi-objective control criterion, possibly using focal plane information.

Organisation of the research work

The PhD student will start with a comprehensive bibliography of XAO control. The CAO control strategies proposed in [9] [10] and other solutions of interest proposed in the literature like [11] will then be implemented in the COMPASS [12] simulator to obtain baseline performance results. This will be done in interaction with European partners of the SAXO+ consortium involved in the Simulation and Control work packages.

New developments will investigate temporal bandwidth error, chromaticity and speckle lifetime from the XAO residual images. Also, a particular attention will be given to the modelling of the disturbance (choice of disturbance basis, structured/non structured models, data-driven identification, update strategies…) to be used for predictive control. The Pyramid WFS is very sensitive but exhibits a nonlinear response which should be accounted for. The design of advanced control will require preliminary studies before being embedded in the simulator and this can be possibly done using the Matlab-Simulink environment. As for multi-objective control, resorting to AI strategies could prove relevant and should thus be investigated (see, e.g., [13] for recent AI developments on reinforcement learning for AO control).

After developing the concepts and verifying them through numerical simulations, the PhD student should confirm the effectivity of the proposed concepts by experiments. ESO’s Adaptive Optics laboratory provides a versatile test environment, the GPU-based High-order adaptive OpticS Testbench (GHOST) testbench [5] , for this purpose.

Institutions

Laboratoire Charles Fabry of the Institut d’Optique Graduate School, Université Paris-Saclay, CNRS, Palaiseau, France

The Institut d'Optique Graduate School (IOGS) is the largest European research and education center in optics-photonics. Education is offered at the engineering and master levels (French SupOptique diplôme d’ingénieur and master’s degrees), and doctoral levels within university doctoral schools. Its research is co-funded by CNRS within the Laboratoire Charles Fabry (LCF, Université Paris-Saclay), Laboratoire Hubert Curien (Saint-Étienne) and Laboratoire Photonique, Numérique et Nanosciences (Bordeaux). The Adaptive Optics (AO) team within the LCF has an internationally recognized expertise for over 20 years in modelling and control for astronomical AO systems, including laboratory and on-sky experiments with demonstrators or operational instruments.

ESO, Garching bei München, Germany
The European Organisation for Astronomical Research in the Southern Hemisphere (ESO) is the foremost intergovernmental astronomy organisation in Europe and the world’s most productive astronomical observatory. ESO operates three unique world-class observing sites in the Atacama Desert region of Chile: La Silla, Paranal and Chajnantor. The ESO headquarters are located in Garching, near Munich, Germany. ESO is the focal point for Europe’s participation in the Atacama Large Millimeter Array (ALMA) consortium, which is currently constructing a large submillimetre array in the Chilean Andes. The concept and design of the ELT is also currently underway at ESO.

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