High-Contrast Integral Field Spectrograph (HCIFS): multi-spectral wavefront control and reduced-dimensional system identification

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Abstract: Any High-contrast imaging instrument in a future large ground-based or space-based telescopes will include an integral field spectrograph (IFS) for measuring broadband starlight residuals and characterizing the exoplanet’s atmospheric spectrum. In this paper, we report the development of a high-contrast integral field spectrograph (HCIFS) at Princeton University and demonstrate its application in multi-spectral wavefront control. Moreover, we propose and experimentally validate a new reduced-dimensional system identification algorithm for an IFS imaging system, which improves the system’s wavefront control speed, contrast and computational efficiency.

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1. Introduction

Several High-contrast imaging instruments have been implemented in large ground-based telescopes, as well as being proposed for future space telescopes, for imaging faint exoplanets and characterizing their atmosphere compositions. [1–3] A high-contrast imaging instrument, as shown in Fig. 1, mainly consists of a coronagraph and an adaptive optics (AO) system: the coronagraph [4–8] suppresses starlight that disguises the planet signals, and the AO system [9–11] corrects the residual starlight speckles caused by Earth’s atmospheric turbulence or the telescope’s optical aberrations. Typically, a high-contrast imaging instrument can achieve $10^{-5} - 10^{-6}$ contrast in ground-based telescopes [12, 13] and is predicted to allow $10^{-9} - 10^{-10}$ contrast in future space telescopes [14, 15]. To study the chemical composition of a planet’s atmosphere, a high-contrast instrument needs to operate in a wide bandwidth to obtain the planet’s absorption spectrum. The broadband starlight field also needs to be measured for wavefront aberration corrections. An efficient approach to achieve both goals is integrating the high-contrast instrument with an integral field spectrograph (IFS).

An IFS is an optical instrument that combines spectrographic and imaging capabilities. Unlike a classical slit spectrograph, an IFS disperses the multi-spectral light in the entire field-of-view (FOV), so the entire broadband starlight field can be measured at once and the potential planet signals can be extracted without prior knowledge of their positions. An IFS has been widely implemented in current large ground-based telescopes, such as OSIRIS [17] for the Keck Telescope, GPI IFS [18] for the Gemini Telescope, CHARIS [19] for the Subaru Telescope, and has been preliminarily tested for space telescopes in lab, such as PISCES [20, 21] at NASA’s Jet Propulsion Laboratory (JPL) Caltech.

In this paper, we will present our recent development of a high-contrast IFS (HCIFS) at
Coronagraph Instrument
Adaptive Optics
Aberrated
Wavefront
(b)
Corrected
Wavefront
Deformable
Mirror (DM)

Imager &
Spectrograph
Adaptive
Optics
Coronagraph
Instrument
Telescope

Fig. 1. Architecture of an example high-contrast instrument at Princeton’s High-Contrast Imaging Laboratory. The coronagraph instrument uses (a) a shaped pupil mask [4] to reshape the (b) point spread function (PSF) and create symmetric high-contrast regions (or so-called dark holes) in the image plane. However, the coronagraph is very sensitive to wavefront aberrations, which cause light leakage into the dark holes and decrease the contrast. The adaptive optics system corrects the complex wavefront aberrations (both phase and amplitude aberrations) using deformable mirrors [16] to maintain the high contrast. The multi-spectral images are measured by an imager or a spectrograph. Here we show a photo of the high-contrast integral field spectrograph (HCIFS), which is a lenslet array-based IFS for simultaneously imaging and spectroscopy.

Princeton’s High-Contrast Imaging Lab (HCIL), dedicated for prototyping the AO for future space-based high-contrast instruments. More specifically, we will focus on the IFS-based multi-spectral wavefront control with imperfect system modeling. Since multi-spectral wavefront control typically requires high-dimensional state-space modeling of the optical system, i.e., requiring large storage and many on-board computational resources, here we propose and experimentally validate a reduced-dimensional system identification method for adaptive multi-spectral wavefront control. The experimental results from HCIL have demonstrated that our new method enables online model error correction, so it improves the multi-spectral wavefront control speed and the achievable contrast of the high-contrast instrument. It also justifies the feasibility of using a reduced-dimensional model for adaptive optics.

2. HCIFS: optical design and data cube extraction

In this section, we overview the optical design of HCIFS and explain the pipeline for retrieving monochromatic images from HCIFS’s broadband measurements.

As shown in Fig. 2, HCIFS is a lenslet array-based IFS. It mainly consists of three parts, (a)(b) a lenslet and pinhole array, (c)(d) a set of dispersion optics and (e) a CCD camera. The lenslet and pinhole array first down-samples the focal plane light field to a sparse field, then the prism disperses the light in the entire FOV and finally the CCD camera records the dispersed image. As a result, the 3-D (x, y and wavelength) broadband image is encoded as a 2-D spatio-spectral
image on the detector. The initial down-sampling prevents crosstalk among spectra at different locations. Specifically, the lenslet and pinhole array of HCIFS is designed to sample the incident field at a Nyquist sampling rate, i.e., there are two lenslets per $\lambda/D$ (wavelength-aperture size ratio). The FOV of HCIFS is $47 \times 39 \lambda/D$. The disperser has a two-component design (a Zinc Sulfide prism and a fused silica prism), which achieves a spectral resolution of 13.2 nm. HCIFS operates at 600 nm to 720 nm ($120\text{nm}/660\text{nm} = 18\%$ bandwidth). More details of HCIFS’s optical design are presented in references [23,24].

The dispersed image is approximately a linear superposition of all monochromatic fields.
Wavefront control is a model-based stochastic control problem. Here we only consider correcting where $\mathbf{E}$ is the HCIFS dispersed image, $\{I_{\lambda_j}\}$ are the reconstructed monochromatic images, $N$ is the number of sampled wavelengths and $\{P_{\lambda_j}\}$ are the corresponding monochromatic flat field templates. This regression problem is typically referred to as “data cube extraction” [25] in IFS image processing. The flat field templates are measured by giving monochromatic input fields over the full bandwidth. Figure 3 shows a HCIFS data cube extraction result of a contaminated coronagraph PSF. Five slices of the reconstructed data cube are displayed. The monochromatic PSF slightly scales up as the wavelength increases, which agrees with Fourier optics that PSF size is proportional to light wavelength. The reconstructed image cube can be then utilized for the following broadband wavefront control and reduced-dimensional system identification.

3. Methods: broadband control and reduced-dimensional system identification

Wavefront control is a model-based stochastic control problem. Here we only consider correcting the non-common-path-error (NCPA) in space-based AO or ground telescopes’ extreme AO systems. In this case, the wavefront control only uses the image plane camera (or IFS), but no extra wavefront sensors, for measuring the fast-enveloping atmospheric turbulence.

The focal plane electric field of a high-contrast instrument can be represented as a linear state-space model [26], as discussed in Appendix A,

$$E_{f,k} = E_{f,k-1} + G\Delta u_k,$$  \hspace{1cm} (2)

where $E_{f,k}$ is the focal plane field, $G$ is the Jacobian matrix, $\Delta u_k$ is the DM control voltage command and $k$ is the time step. By concatenating the electric field and Jacobian matrices at different wavelengths, $E_{f,k}^\lambda$ and $G_{\lambda}$, we can derive a state space model for the broadband electric field,

$$E_{f,k}^b = E_{f,k-1}^b + G_b\Delta u_k,$$  \hspace{1cm} (3)

where $E_{f,k}^b = [\cdots ; E_{f,k}^{\lambda_1}; \cdots ]$ and $G_b = [\cdots ; G_{\lambda_1}; \cdots ]$. The intensity of the electric fields are measured by the IFS reconstructed monochromatic images (Eq. 1),

$$I_{f,k}^b = [\cdots ; I_{\lambda_1,k}; \cdots ] = |E_{f,k}^b|^2 + I_{in,k}^b,$$  \hspace{1cm} (4)

where $I_{in,k}^b$ is the incoherent background, such as stray light or planet signals.

With the state-space model (Eq. 3) and the observation model (Eq. 4) defined, the wavefront control loop can be closed by first estimating the electric field based on the images, and then computing the DM command that removes starlight speckles and maintains a high contrast.

Electric field estimation applies maximum likelihood estimation (MLE) methods, including batch process least squares regression [27–29], Kalman filtering [30] or extended Kalman filtering [31, 32]. It collects measurements by introducing various DM sensing commands, and solves for the hidden electric field by minimizing the difference between measurements and model predictions as well as constraining the solution close to the electric field of the last step. For example, the extend Kalman filter computes the hidden electric field via

$$\min_{E_{f,k}^{b,1:\text{obs}}, I_{in,k}^b} \sum_{m=1}^{N_{\text{obs}}} \left\| I_{f,k}^b - |E_{f,k}^b|^2 - I_{in,k}^b \right\|_R^2 + \beta_k \left\| E_{f,k}^b - \bar{E}_{f,k}^b \right\|_Q^2$$

s.t. \hspace{1cm} $E_{f,k}^{b,m} = E_{f,k}^b + G_b\Delta u_k^m, \hspace{1cm} \forall m = 1, \cdots, N_{\text{obs}}$

$$E_{f,k}^b = E_{f,k-1}^b + G_b\Delta u_k,$$  \hspace{1cm} (5)
where $p_{b,m}^k$ and $E_{f,k}^{b,m}$ are, respectively, the sensing images and sensing fields, $E_{f,k}^b$ is the electric field prediction based on last step, $\Delta a_m^k$ are the DM sensing commands, $N_{obs}$ is the number of sensing images, $\| \cdot \|_R$ and $\| \cdot \|_Q$ are the two weighted norm, and $\beta_k$ balances the measurement term (or so-called data fidelity term) and the prior knowledge term.

Wavefront controllers then use the estimated electric field to find the optimal control command. Common wavefront controllers include electric field conjugation (EFC) [27, 33], stroke minimization (SM) [34] and robust linear programming controller (RLPC) [35]. For example, EFC is a quadratic controller that minimizes the starlight speckle intensity,

$$
\min_{\Delta u_{k+1}} \| E_{f,k}^b - G_b \Delta u_{k+1} \|_2^2 + \alpha_k \| \Delta u_{k+1} \|_2^2,
$$

where $\alpha_k$ is the Tikhonov regularization parameter that prevents unreasonably large control command. Looping the above estimation and control steps, the contrast is gradually improved and finally maintained at a high level for scientific observations.

Both the electric field estimation and the wavefront control require an accurate system model (Eq. 3). However, in a real instrument, manufacturing errors, mis-calibrations and thermal effects always cause mismatches between the real system and the state-space model. Recently, a machine learning approach has been developed to achieve system identification using real-time wavefront control data. [36, 37] This approach uses an E-M algorithm, which iteratively reconstructs the hidden electric field (E-step) and updates the state-space model (M-step). The E-step is identical to the electric field estimation as in Eq. 5, where the model is assumed known and the hidden electric field is estimated; the M-step, to the contrary, minimizes an almost the same cost function with respect to the model parameters assuming known a electric field (constraints are omitted),

$$
\min_{G_b} \sum_{m=1}^{N_{obs}} \| p_{b,m}^k - (E_{f,k}^{b,m})^2 - R_{l,m,k} \|_R + \beta_k \| E_{f,k}^b - \bar{E}_{f,k}^b \|_Q^2.
$$

This approach has been demonstrated in experiment for monochromatic wavefront control.

In this paper, we adapt this algorithm to the IFS-integrated high-contrast imaging instrument. Since the system controls the wavefront of multiple wavelengths and thus a high-dimensional state-space model is required, here we propose to improve the computational efficiency by combining the current machine learning method with a model reduction technique. Instead of using a full rank Jacobian matrix, we represent the Jacobian matrix as combining the current machine learning method with a model reduction technique. Instead of a high-dimensional state-space model is required, here we propose to improve the computational efficiency by combining the current machine learning method with a model reduction technique. Instead of using a full rank Jacobian matrix, we represent the Jacobian matrix as

$$
\min_{U,V} \sum_{m=1}^{N_{obs}} \| p_{b,m}^k - (E_{f,k}^{b,m})^2 - R_{l,m,k} \|_R + \beta_k \| E_{f,k}^b - \bar{E}_{f,k}^b \|_Q^2
$$

s.t. $E_{f,k}^{b,m} = E_{f,k}^b + UV^T \Delta a_m^k$, \quad \forall m = 1, \cdots, N_{obs}

and $E_{f,k}^b = E_{f,k-1}^b + UV^T \Delta u_k$.

This would be extremely beneficial for future thirty-meter size ground-based telescopes and large space telescopes that have DMs with more than ten thousand actuators and aim for large high-contrast observation areas in the image plane. We experimentally test this reduced-dimensional system identification and the resulting wavefront control in Sec. 4.

4. Results and discussion

The experiments are conducted using Princeton’s HCIL testbed, whose layout is shown in Fig. 4. It utilizes a ripple pupil-plane mask (as shown in Fig. 1 (a)) to create high-contrast observation.

\footnote{It is not exactly the same. The M-step should be a stochastic optimization problem instead of a deterministic optimization problem, because the electric field is a probability distribution from estimation instead of a fixed value. Please see reference [36, 37] for more details.}

\textbf{References}
The list of devices: 1. laser, 2. baffle, 3. first off-axis parabola (OAP1), 4. fold mirror, 5. DM1, 6. DM2, 7. shaped pupil mask (SP), 8. second off-axis parabola (OAP2), 9. focal plane mask (FPM), 10 and 11. reimaging lenses, 12. CCD camera, 13. focusing lens, 14. integral field spectrograph (IFS), 15. pick-off mirror.

regions. In addition, a bowtie-shaped focal plane mask (as shown in Fig. 5 (c)(d)) is used to block the central bright part of the PSF to avoid camera saturation. A pair of continuous surface MEMS DMs from Boston Micro-machines Corporation (BMC) [16] are used to correct the wavefront aberrations in the system. Each DM has 952 actuators. A Koheras SuperK Compact super-continuum laser source (equipped with eleven narrow-band filters and one broadband filter) is used for simulating the multi-spectral starlight. We also have two detectors on the testbed, a CCD camera and the HCIFS, between which we can switch using a pick-off mirror. In all our experiments, we use Python package “CRISPY” [22] to extract the monochromatic images from IFS measurements. The broadband state is defined by an electric field at five representative wavelengths, 615nm, 634nm, 654nm, 674nm, 695nm. Our control law tries to improve the contrast in two symmetric sectors of the images (as shown in Fig. 5) with a 60 degree angular range and a $3 \lambda/D$ width (6 to 9 $\lambda/D$ from the center).

The rank of the reduced Jacobian matrix is 400. (a) Measured, modulated and incoherent contrast versus control step after three system identification trials. (b) Modulated contrast versus control step after each system identification trial. (c) Original and (d) corrected HCIFS dispersed images. As can be seen, the wavefront control becomes faster and achieves higher contrast after system identification. The reduced-dimensional model performs robust wavefront control.
Figure 5 shows the wavefront control and system identification results where we only keep 400 modes of the Jacobian matrix, i.e. the rank of matrices $U$ and $V$ are constrained to be 400. The test was run as follows: we run wavefront control for ten loops with a fixed Jacobian matrix, then we update the Jacobian matrix using the reduced-dimensional E-M algorithm and run another ten steps of wavefront control using the updated model, repeating until the wavefront correction no longer improves (not faster or achieving higher contrast). Figure 5 (a) reports the contrast-versus-control step curve after the model accuracy converges. Three lines respectively represent the broadband measured contrast, the modulated contrast (the starlight contrast which can be influenced via wavefront control) and the incoherent contrast. All three contrasts are computed by averaging over the five representative wavelengths. Currently, our IFS-based high-contrast imaging instrument is mainly limited by the incoherent light (mainly from the laser fiber). Figure 5 (b) shows the modulated contrast curve after each system identification trial. With system identification, the wavefront control reaches a high contrast with fewer control steps and achieves a higher final contrast compared with the experiment using the original biased model. The correction speed and contrast stop improving after around three system identification trials.

Fig. 5. Wavefront control and system identification results (a) Contrast versus control step. (b) Contrast over bandwidth. (c) Comparison of the final achievable contrast and singular values. The contrast is approximately linearly related to the singular value at the specific number of modes, so the reduced model’s rank can be determined based on the desired system’s contrast.

In Fig. 6, we report the wavefront control results after three system identification trials with different numbers of modes. Reducing the number of modes influences the final contrast of the system. Figure 6 (c) compares the final contrast and the singular values of the full-rank Jacobian matrix. As can be seen, the contrast is approximately proportional to the cut-off singular value, so a reasonable number of modes for the Jacobian matrix can be selected according to the instrument’s target contrast. The final contrast stops improving with more than 400 modes. This is likely because our system’s achievable contrast is limited by the bright stray light, since the accuracy of electric field estimation will be highly influenced by the stray light photon noises. Our future work is focusing on reducing the stray light in the instrument, such as replacing the laser fiber and introducing a spatial filter.

5. Summary

In this paper, we have reported our development of a high-contrast integral field spectrograph (HCIFS) for a telescope’s high-contrast imaging instrument and a multi-spectral wavefront control approach and results. Moreover, we propose a reduced-dimensional system identification method for improving the instrument’s modeling accuracy. Experimental results demonstrate that the identified reduced-dimensional model improves the system’s wavefront control speed,
final contrast and computation efficiency.

**Appendix A  State-space modeling of a high-contrast imaging instrument**

As shown in Fig. 1, with the aberrated incident wavefront, the DM surface deformation, the corrected pupil plane wavefront, the coronagraph mask, the image planet field denoted as $E_{ab}$, $\phi$, $E_p$, $M_p$ and $E_f$ respectively, we have

$$E_p = E_{ab} \exp(i \frac{4\pi \phi}{\lambda}),$$
$$E_f = \mathcal{F}\{M_p E_p\},$$

(9)

where $\mathcal{F}\{\cdot\}$ is a Fourier transform operator. The mirror deformation is approximately a linear superposition of each actuator’s influence,

$$\phi = \sum_{q=1}^{N_{act}} u_q f_q,$$

(10)

where $N_{act}$ is the number of actuators on the DM, $q$ is the actuator index, $u_q$ is the DM voltage command, and $f_q$ is a single actuator’s influence on the DM surface deformation (referred to as the DM influence function). Writing the DM voltage command as a time-cumulative formula,

$$u_q = u_{q,k} = u_{q,k-1} + \Delta u_{q,k},$$

(11)

we can derive a linear state transition model (combining Eq. 9, Eq. 10 and Eq. 11) assuming the DM adjustment at each step is small (typically even accumulated DM adjustments are only a few tenths of wavelength),

$$E_{f,k} = \mathcal{F}\{E_{ab} M_p \exp(i \frac{4\pi \sum_{q=1}^{N_{act}} (u_{q,k-1} + \Delta u_{q,k}) f_q}{\lambda})\}$$
$$\approx \mathcal{F}\{E_{ab} M_p \exp(i \frac{4\pi \sum_{q=1}^{N_{act}} u_{q,k-1} f_q}{\lambda})[1 + i \frac{4\pi \sum_{q=1}^{N_{act}} \Delta u_{q,k} f_q}{\lambda}]\}$$
$$= E_{f,k-1} + \sum_{q=1}^{N_{act}} \frac{i4\pi E_{f,k-1} \mathcal{F}\{f_q\}}{\lambda} \Delta u_{q,k}$$
$$\approx E_{f,k-1} + \sum_{q=1}^{N_{act}} \frac{i4\pi \mathcal{F}\{E_{ab} M_p f_q\}}{\lambda} \Delta u_{q,k}.$$

This can be denoted as a standard state-space formula,

$$E_{f,k} = E_{f,k-1} + G\Delta u_k$$

(13)

where $\Delta u_k = [\Delta u_{1,k}, \cdots, \Delta u_{N_{act},k}]$ and $G$ is the Jacobian matrix computed from $E_{ab}$, $M_p$, $f_q$ and $\lambda$. Electric fields at different wavelengths have different state space response.

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