Coupling Control of a Telescope Focus into a Single-Mode Optical Fiber Based on a Reference Model Controller

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***Abstract*—We propose and demonstrate a low-cost magneto-mechanical fiber micro-positioner for optical coupling, with a square-millimeter working range and a resolution of a few microns per pixel. We demonstrate the functionality of the positioner as a beam pattern imaging system for a 14" Dobsonian telescope as it is compact enough to be mounted instead of a small-telescopes eye-piece. The aim is to use this positioner to couple and stabilize a telescope beam to a single-mode fiber. We make a first approach to a reference model controller showing an increase of the average coupled power under perturbations from 54% to 85%.**

***Keywords*—Fiber optics, infraredFibers, single-mode, Pattern recognition, Optomechanics, Alignment, Astronomical instrumentation, Beam coupling**

I. Introduction

Environmental perturbations are a fundamental problem in every area that includes light transmission and reception, as in telecommunications and astronomy. This noise affect directly the light power needed, thus the error rate, velocity and accuracy of a telecommunication system [1]. Fiber optics is considered a reliable medium for light waves and is widely used in telecommunications and optical systems, because of its high bandwidth and low losses. Still, wireless connection will be preferred in many cases rather than wired communications [2].

Even though wireless and fiber-optics communications are used in parallel nowadays, there are few implementations of direct coupling from a traveling laser beam to a fiber in a system including a dynamic atmosphere. This is due to the technical difficulties related to coupling a signal into a optical fiber, even in the case of a static system with multi-modes fiber, which have wider core diameter than single-mode ones. Thus, the challenge of our project consists in developing a system able to couple a traveling wave into a single-mode fiber for static and dynamic systems in order to extend the use of this technology.

The design we introduce in this paper was devised as a functional component of an astronomical fiber-based infrared heterodyne interferometer we previously proposed [3] [4]. Aiming to compensate atmospheric turbulence distortions (seeing) in the diffraction-limited focus of small telescopes. The idea of using single-mode fibers in long-baseline optical and near-infrared interferometers was discussed for the first time some decades ago, including the correction of atmospheric distortions [5]. However, besides the mentioned mathematical revision, no control has been implemented to improve the fiber coupling efficiency.

The idea is to use a compact telescope to focus the beam into the fiber. In large aperture telescopes, adaptive optics (AO) is necessary to correct the wave front and therefore obtaining the highest possible coupling-efficiency, but then, a coupling controller is still useful to slowly position the fiber in the corrected focus.

For smaller telescope diameters (d < Fried-parameter) the

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distortion is, to a high degree, only a movement of the emitter image in the focal plane, e.g. to 80% for the 35 cm-diameter telescope we use here [6]. Hence, it is assumed that, as a cheaper approximation to AO, a "tip-tilt correction" is sufficient. Tip-tilt corrections are commercially available, implemented with a tip-tilt-actuated optically refracting plate or mirror. However, their large optical aperture is only needed for camera applications but not for the "single pixel" of a fiber.

Considering the scenarios mentioned above, we divided our system in two parts: a static scan used to recognize the beam pattern and as a first coupling step, and a dynamic control in order to be used in noisy environments. For this purpose, instead of using two piezo actuators to move the optical fiber, we decided to use the lens actuator from a compact-disk drive, which is described in section II-A.

II. Design of the positioning system

A. Beam pattern recognition

The device used as actuator is an electromagnetic based system taken from a CD Drive. Basically, a voice coil with permanent magnets which make use of the Lorentz force to move the stage in X and Y axis. These magneto-mechanical actuators have a two-dimensional motion range in the order of 5mm×5mm and are driven by -5 to 5 Volts signals, with currents up to $300m$A.

A fiber ferrule was fixed to the device so it can be moved freely. In order to get a static scanning, the actuator's range was divided into steps and the power of the incident beam was measured in each step, generating a matrix of power values.

B. Controller System

Due to the use of a single-mode fiber, the received power is very sensitive to the position of the beam relative to the center of the fiber, but doesn't give any information of the position of the beam in the XY plane, because of its geometry. Thus, this signal cannot be used as a control signal and a reference model is needed.

The reference model used is a quad photodiode (QPD) that receives the signal with a small defocusing to widen the beam in order to get the control signal in both axes. This reference model is broadly used and documented [7] [8] [9]. From [7] it is possible to calculate the position of the center of the beam as:

$$u_x=\frac{(\rho_1+\rho_2+\rho_3+\rho_4)[cos^{-1}(\frac{x}{r})-\frac{x}{r}\sqrt{1-(\frac{x}{r})^2}]-(\rho_2+\rho_3)\pi}{(\rho_1+\rho_4-\rho_2-\rho_3)[cos^{-1}(\frac{x}{r})-\frac{x}{r}\sqrt{1-(\frac{x}{r})^2}]+(\rho_2+\rho_3)\pi} \tag{1}$$

$$u_y=\frac{(\rho_1+\rho_2+\rho_3+\rho_4)[cos^{-1}(\frac{y}{r})-\frac{y}{r}\sqrt{1-(\frac{y}{r})^2}]-(\rho_3+\rho_4)\pi}{(\rho_1+\rho_2-\rho_3-\rho_4)[cos^{-1}(\frac{y}{r})-\frac{y}{r}\sqrt{1-(\frac{y}{r})^2}]+(\rho_3+\rho_4)\pi} \tag{2}$$

Where r is the radius of the beam, ρ_i is the photoelectric conversion coefficient of the photo-diode i and (x, y) are the coordinates of the center of the beam relative to the center of the QPD. The range of interest for both equations 1 and 2 is $x, y < r$.

Nevertheless, considering small oscillations, a linear approximation can be made. Thus, the position of the center of the beam can be calculated as follows:

$$u_x = \frac{[u_2+u_3]-[u_1+u_4]}{u_1+u_2+u_3+u_4} \tag{3}$$

$$u_y = \frac{[u_4+u_3]-[u_1+u_2]}{u_1+u_2+u_3+u_4} \tag{4}$$

where u_i is the total power measured in the photo-diode i, $u_i = \int \rho_i$. For our experiment, this linear approximation was used so far.

C. Model and Control design

The model of the actuator used have been widely documented [10]–[13] as is used to ensure the stability of the Optical Disk Drive System. Guided by [11], where the actuator is modeled as a second-order system of mass-spring-damper, the transfer function of the actuator is:

$$F(s) = \frac{K_t}{a_3s^3+a_2s^2+a_1s+a_0} \tag{5}$$

with

$$\begin{aligned} a_0 &= k_f R_a \\ a_1 &= d_f Ra + k_f L_a + K_t K_{emf} \\ a_2 &= m_f R_a + d_f L_a \\ a_3 &= m_f L_a \end{aligned}$$

where K_t is the Force constant, R_a and L_a are the Resistance and Inductance of the voice-coil actuator, K_{emf} is the motor constant (EMF constant) and m_f, k_f and d_f are the mass, spring constant and the damper function of the actuator. Note that the complexity of the system is mainly because the Inductance was not neglected as the system will be use at high frequency.

With the model, a Linear Quadratic (LQ) Controller was designed in order to have a proportional controller with the feedback system explained in section II-B. For further tuning, the parameters of the LQ Controller can be optimized using MATLAB.

III. Experimental testing

The proposed system was tested in two different measurement setups. First, a static setup in the focus of a telescope was done to demonstrate digitally controlled positioning accuracy. Then, an optical table experiment was mounted for testing the Control System.

A. Experimental Setup

The system was built to be used in the focus of arbitrary telescopes. For this goal, we alternated between a 8″-Schmidt-Cassegrain and a 14″-Dobsonian as a beam collimator for launching a single-mode fiber signal from a single-mode DBR-diode laser into a collimated beam (quasi-plane wave). The beam was sent over 36 m along a corridor to a 14″, $f/\# = 4.5$ ($f = 1.65$ m), motorized Dobsonian telescope

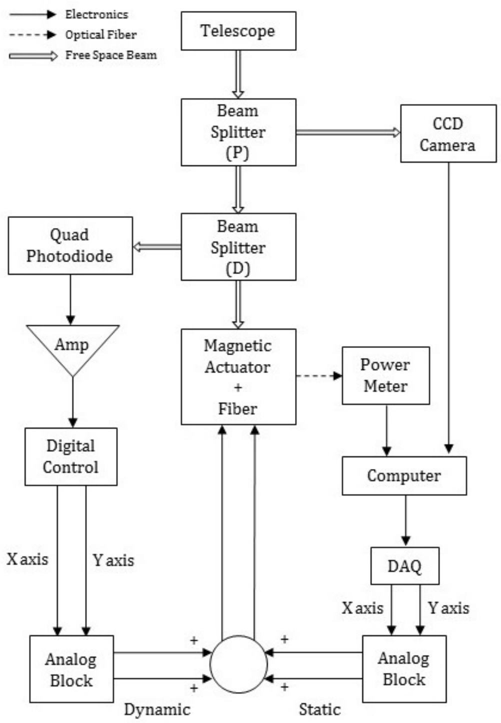

Fig. 1. System Schematic including Circuits and Optics. Solid lines are electronics connections, the dotted line is an optical fiber and the double solid lines are free beam paths.

from Orion Telescopes, and coupled into the ferruled fiber in its focal plane, using the integrated actuator module. The central blockage diameter due to the telescope pickup mirror is $d_{obs} = 80$ mm. The coupled power was measured for a matrix of (x,y)-positions of the actuator using a fiber Powermeter (Thorlabs PM1000 with sensor head S155C), and saved using a LabView script.

To simplify optical alignment, a 50% beam splitter cube with a CCD camera was added in front of the fiber coupler to have a first centering step. After the first beamsplitter, a dichroic beamspliter (Thorlabs DMLP1180 with cut-off frequency of 1180 nm) was used to separate the signal that goes to the fiber from the one entering to the reference model. We chose a dichroic beamspliter not to diminish the incident power in the frequency range of interest (near-infrared).

For the mapping, the output signal to move the actuator was processed in a NI6008 National Instrument Data Acquisition Board (NI DAQ). This plus the Powermeter data were controlled from a LabView programmed graphical user interface (GUI). On the other hand, the controller was based in an Microchip PIC18f-family micro-controller. Both systems have their respective analog circuits to ensure Inputs and Outputs work in the required range. Hence, the actuator receives the sum of both systems.

For the second experiment, the controller was tested in an optical table. With the purpose of emulating slow perturbations, a near-infrared laser (QSDIL-300 from QPhotonics with $\lambda_{peak} \approx 785$nm) was connected to a fiber mounted in another CD magneto-mechanical actuator, driven by a sinusoidal signal generator. The oscillating laser beam follows an optical path to finally be focused into the receiver fiber. Using the same receiver system explained before - no changes were done in its architecture - we measured the power coupled to the optical fiber both with the controller running and turned off.

IV. Results

A. Beam Pattern Scanner

To have an accurate beam pattern scan, first a total range map is made. Then, successive zoomed maps are measured in order to achieve higher definition. In figure 2 we show the first map and figures 3 and 4 show two consecutive closeups. To evaluate the shape of the beam, a 2D map was plotted (figure 5). For this purpose, a 1.35mm $\times$1.35mm scan with steps of 21μm was enough to characterize the beam. The result was an elliptical pattern with $R_1 \approx 693\mu$m and $R_2 \approx 420\mu$m. As the NI DAQ used has a 12 bits DAC, the minimum possible step is 2.5 mV which corresponds to 1.22μm. As a consequence, the minimum map of 32×32 resolution can be about 390 μm $\times$ 390 μm. This confirms definition is very relevant.

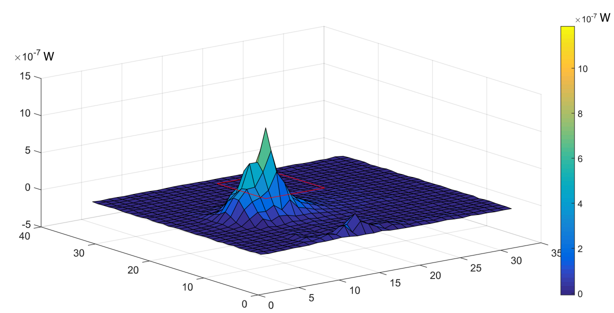

Fig. 2. Full range map. 32×32 pixels. Each step is 156μm. The red square marks the first closeup to be done, shown in figure 3.

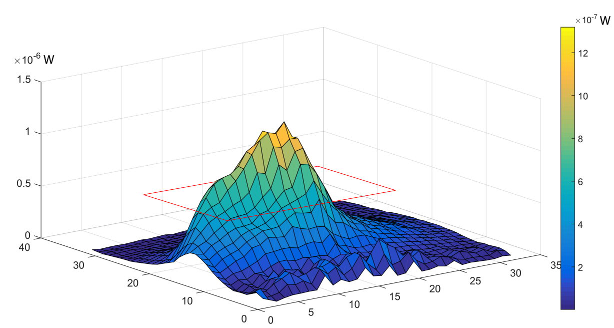

Fig. 3. First zoomed map. 32×32 pixels. Each step is 85μm. The red square marks the second closeup to be done, shown in figure 4.

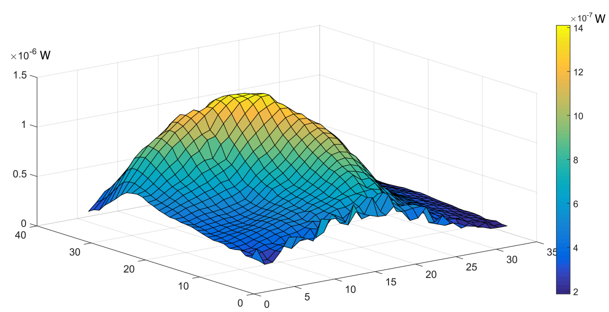

Fig. 4. Last zoomed map. 32 × 32 pixels. Each step is 41μm.

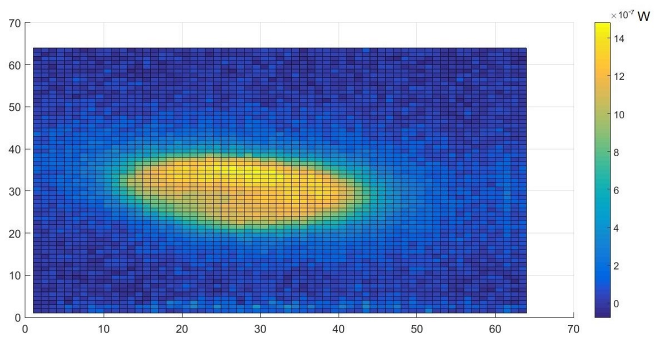

Fig. 5. 2D plot of high resolution zoomed map. 64 × 64 pixels. Each step is 21μm. Elliptical beam pattern with $R_1 \approx 693\mu$m and $R_2 \approx 420\mu$m.

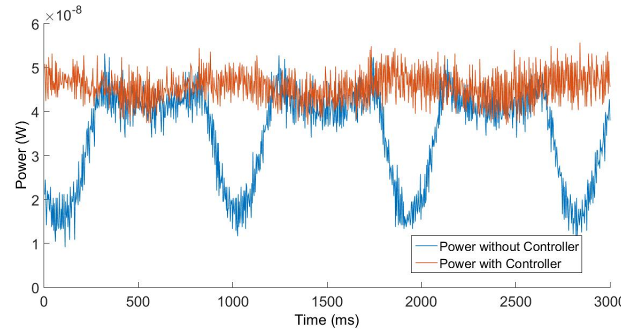

Fig. 6. Coupled Power with (orange) and without (light blue) Controller.

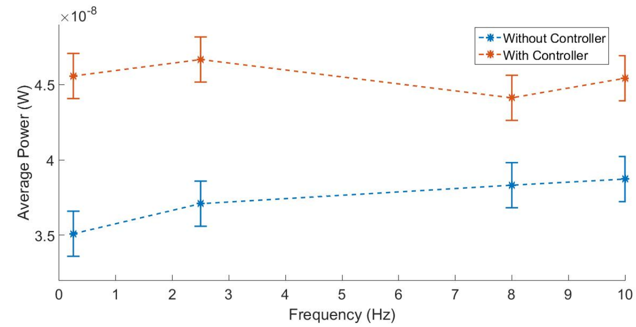

Fig. 7. Average power at different frequencies with (orange) and without (light blue) Controller as shown in figure 6.

The total power of the beam, considering the discretization shown in figure 5 is approximately 630μW, which corresponds to $\approx$81% of the real power. Nevertheless, the maximum coupled power is just 0.22%, as the area of the ellipse is much larger than the "single pixel" of the fiber. We estimate that with a higher precision of focus control this can be improved.

B. Reference model based control system

Figure 6 shows the coupled power with and without the controller working, taking a sinusoidal input signal.
The average coupled power without controller corresponds to 35.1nW and with the controller to 45.6nW. This means an efficiency improvement from 63% to 82% of the maximum coupled power.
The difference between maximum and minimum coupled power is reduced from 53.9nW to 20.5nW. The oscillation of the coupled power with the controller is attributed to a non-optimized tuning, misalignment in the optical path and the non-linearity of the reference model. In section V, possible improvements of the system are discussed.
We also measured the efficiency of the controller at different frequencies of oscillation and the results are shown in figure 7. The average power without the controller increases with the frequency because the movement of the laser emitting actuator is reduced as frequency grows. To compensate this and have a constant perturbation amplitude, currents out of the device specifications should be applied to the CD Drive. Besides, the decrease on the efficiency of the controller is attributed to the parameters tuning, which need to be optimized for each point. Higher frequency measurements could not be reached due to the Powermeter's ADC velocity.

V. Conclusion

The possibility of building a focal beam scanning system for micro-metric purposes using low cost elements was demonstrated.
The great advantage of the system is that the fiber position can be changed by the user in real time activating and deactivating the controller. We also demonstrate that the definition is high enough to freely manipulate the coupling position in a static scenario like optical table alignment, with a low cost system. In the dynamic system, we demonstrate a controller working properly but not fast enough. For this, we are working in system upgrades using a MEMS mirrors based system, in order to get a closed loop control system. Also, a focus controller is being studied.
This actuator gave us the opportunity to study the alignment of a telescope focal beam to an optical fiber, a problem which was not well described in literature, as we could not find an experimental verification of the predictions of Horton [14] and Ruilier [15]. Finally, it is a reliable tool for static systems and a suitable first approach for dynamic systems.

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