ParFAIT: Partially Filled Aperture Interferometric Telescope

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Concept: Large optical quality mirrors can be made from fire-polished glass without abrasive polishing using additive technologies. We will replace conventional mirror substrate mass, that would normally be necessary for mechanical stiffness, with active 3-D printed sensors and actuators on accurately shaped paraboloidal glass substrates. With such hybrid structures, the net areal mass density can be an order of magnitude less than a conventional light-weight mirror with a diffraction-limited optical surface. These low-mass mirrors enable large optical surfaces to be economically created to approximate a parent paraboloid. The mass of the underlying multi-mirror support structure can be further reduced with a relatively "soft" global support structure. ParFAIT's optical configuration combines off-axis paraboloid segments with an ensemble of small elliptical secondary mirrors such that all optical beams share a common focus. Each elliptical secondary mirror is illuminated by one primary mirror segment, and becomes its steering and phasing element. In this way each beam is combined coherently at the Gregorian focus of the larger, two-axis tracking, primary parent optics without interferometer delay-lines. This optical system achieves the full angular resolution of the parent while efficiently matching the "softness" of the mechanical structure to the atmospheric piston phase fluctuations. ParFAIT has good optical modulation transfer function (MTF) properties, and approaches the photometric dynamic range sensitivity of a filled-aperture 100m-class optical system. We believe a 100m ParFAIT can be constructed for about \$150M with 39 5mx5m hybrid mirror segments in a "cross" configuration. A small proof-of-concept built from five 0.5x0.5m hybrid mirror segments is proposed for Haleakala, adjacent to the AEOS AF and University of Hawaii facilities. It will demonstrate the technology for hybrid glass mirrors and the secondary mirror phasing concept. This mini-ParFAIT could be developed and deployed during a 12 month research and development program. We note that ParFAIT has a field-of-view that is limited to a few arcsec by its primary optical system. Depending on seeing conditions, ParFAIT operates with a 13 magnitude or brighter source within its field-of-view, although artificial optical sources could mitigate this limitation.

Objective 1, Meter-class Low Cost Optics: Glass is an ideal reflector material as it is stiff, hard, relatively cheap, and can be formed into large and smooth flat pieces. Mirrors are created by stamping, molding, or grinding processes – the latter can produce high-precision surfaces but at a slow rate and high cost (typically ~\$0.3M/m^2) that is one limitation of large aperture optical systems. Unfortunately, the former techniques involving heating glass to shape it, for example against a mandrel, tend to create a rough (non-specular) surface with significant surface shape errors. For large reflective surfaces the cost of the mandrel and reproduction process also overwhelm the economics of creating large mirrors. Thin glass mirrors require a stiff and usually heavy substrate or mount to maintain their accurate optical-quality surface against gravity deformation. Such large image-quality mirrors built as monoliths or with integral support structures typically weigh 500 kg/m^2 [1]. We will reduce the mass of large mirrors by creating artificial hybrid structures with active force sensors and actuators built into a sandwich of thin paraboloidal glass plates. Our starting point is ordinary flat fire-polished float-glass with excellent microroughness scattered light properties that are an order of magnitude better than conventional abrasively polished glass.

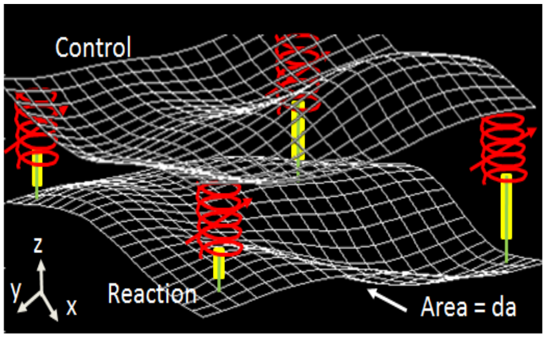

Figure 1: A schematic of a hybrid structure illustrates a sandwich of warpable surfaces (upper and lower white grids) separated by a lattice of force actuators (red) in series with force transducers (yellow). The upper and lower elements are the control and reaction surfaces. Actuator forces are independently determined by metrology of the top surface shape. The actuator geometry illustrated here assumes only a vertical external force with a substantial lateral material stiffness in the actuators.

The top surface shape is not dependent on the stiffness of the lower surface of the hybrid because the force distribution defines the surface shape. The reaction surface need only be stiff enough to accommodate the displacement range of the actuators that are pushing/pulling with equal and opposite forces against the two plates. Bipodal force elements with force components in the x and y directions are used when the structure is inclined from the vertical direction.

Parabolic glass sheets are formed in a special furnace. We use the theory of thin glass plates (as defined by the Kirchoff-Love equation [2]) in a temperature and pressure controlled environment to form accurate paraboloidal surface sections. This only requires contact with the edge of the glass and the ability to slowly change Young's modulus while affecting the air pressure force distribution on the glass. Large off-axis paraboloids result, with rms shape deviations of less than 50 microns and microroughness less than 1nm. Shape errors are within the dynamic range of the lattice of active control points. The glass is intrinsically smooth and accurately paraboloidal on length scales shorter than the lattice spacing. We call this shaping process "Deterministic Non-Contact Glass Slumping (DNCGS)."

We create hybrid active structures by sandwiching force actuators and sensors between two thin DNCGS surfaces using a gantry system and 3D printing techniques. The starting DNCGS surface is close enough to the final parabolic shape so that the dynamic range of the actuator and metrology system corrects the shape error through the imposed actuator force distribution. Because one m^2 of mirror area requires about 200 force points, 3D printed actuator/sensors are crucial. Our prototype concept uses printable capacitive and spring-force sensors in series with electrostatically actuated ionic electroactive polymers [3]. We expect stand-alone diffraction limited parabolic surfaces with a net areal mass density < 30 kg/m^2 for 5m x 5m mirrors.

Objective 2: Image Formation: Square off-axis parabola sections will be configured within a 70 x 70 x 30m volume into a sparsely sampled parent parabola optic. Figure 2 illustrates the primary and secondary mirror optics of the sparse ParFAIT mirror geometry. The secondary mirror segments are only about 25cm across and each one provides piston phase and tip-tilt wavefront control for one of the 39 5 x 5m parabola primary mirror segments. The secondary segments are adaptive so each 5x5m sub-optic delivers a diffraction limited wavefront to the common Gregorian focus. The ParFAIT optical concept is derived from the Colossus [1] nearly-filled aperture interferometric telescope (see also www.the-colossus.com).

Figure 2. ParFAIT: Square 39 5x5m off-axis paraboloid segments illuminate separate elliptical secondary segments to create a common Gregorian focus near the vertex of the parabolic parent optic. The total length of each cross is 100m with 25x25cm secondary segments.

The ParFAIT pupil is sampled along the diagonals of a 70m x 70m square, This makes it well-suited for detecting low-contrast and barely resolved objects in the presence of a bright on-axis source. Under many circumstances it has high dynamic range with the spatial resolution of the 100m parent aperture. The necessary global mirror phase information for each suboptic is reconstructed from final composite speckle image..

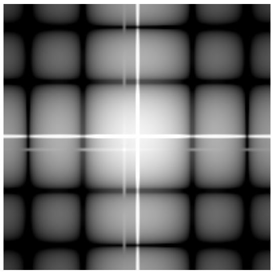

Figure 3: A 0.1 x 0.1 arcsecond simulated noiseless ParFAIT image of a bright central point source and a faint companion. The intensity scale is logarithmic over 10 magnitudes in this display. The off-axis source is 1000x fainter and located 0.005 arcseconds down and to the left from the central object. The pupil mirror geometry creates the horizontal and vertical diffraction spikes but the faint source is readily visible. The ParFAIT PSF resolution for imaging faint objects is effectively the full 100m aperture except in the x-y directions of the optical cross.

Objective 3, Optical Testbed: Two key technologies will be demonstrated with the proposed five 0.5 x 0.5m testbed optical system: 1) controlled hybrid glass structures, yielding diffraction-limited paraboloidal mirror segments will be constructed, and 2) the image-domain mirror phasing beam combiner that is required to create a coherent imaging system from off-axis segmented beams. Using 0.5m primary mirror segments means that 1micron observations from Haleakala will have high Strehl with only tip/tilt mirror correction, so that a deformable mirror AO system for each secondary mirror segment is not required. The five hybrid optics will form a linear segment from a parent parabola with a radius of curvature of 5m. This “mini-ParFAIT” will be temporarily installed on a 2-axis trackerfor testing in a UH observatory building No significant infrastructure modifications are required to complete a 12-18 month research program.

References: **[1]** Kuhn, J.R., et al.: Looking beyond 30m-class telescopes: the Colossus project, Proc. SPIE Astronomical Telescopes & Instrumentation, 9145, id. 91451G 8 pp. (2014); **[2]** Doghri, I.: Mechanics of Deformable Solids: Linear, Nonlinear, Analytical and Computational Aspects pp. 579 Springer (2010); **[3]** Gavrin, A., Blizard K., et al.: Electroactive smart polymers for space optics, Proc. SPIE 5390, Smart Structures and Materials: Smart Structures and Integrated Systems, 217 (2004)