INSTITUTO DE ASTROFISICA DE CANARIAS

GRADUATE STUDIES DIVISION

PROPOSAL FOR PhD PROJECT - 2023

(Do not exceed 4 pages – excluding annexes)

Name of Supervisor (or Supervisors): Jeff Kuhn (IAC)
Name of Co-Supervisor (if there is any): Patricia Fernandez (IAC), Ye Zhou (external)

Name of Tutor (if different from Supervisor):

Title: Developing low-mass, stiff, precise opto-mechanical innovations for future large telescope and space systems

Related IAC Research Project:
The PhD student will benefit from interactions with several groups:
(1) Members of the Laboratory for Innovation in Opto-Mechanics (LIOM)
(2) IAC Optics group
(4) Low-mass, brown dwarf, and exoplanets group at the IAC

Abstract:
The broader goal is to develop novel solutions for addressing the challenging and crucial problem of eventually imaging faint habitable planet's around a star that is typically 7-9 orders of magnitude brighter. The Laboratory for Innovation in Opto-Mechanics (LIOM) is an international collaboration that is building a large (35 m-scale aperture) multi-aperture telescope called the ExoLife Finder (ELF) to achieve this goal. This PhD thesis aims to examine and utilize new tools and techniques like tensegrity that should make it possible to dynamically support low mass, large area multiple sub-apertures that can measure reflected exoplanet light while preferentially suppressing the star light. The ultimate goal of this thesis would be to develop and demonstrate a laboratory opto-mechanical system for supporting and controlling the optical surface of a 0.5m-scale thin mirror optic. The demonstrated performance will allow modeling and a refined evaluation of the co-phasing and interferometric nulling of pupil sub-apertures in the 35m-scale ELF telescope. This technology demonstrator will be implemented on the Small-ELF and will pave the way for detailed design of such capability into the full-fledged 35-m ELF telescope and possibly space-based telescopes requiring low mass optics.

Short List of Goals:

Below is a list of science/technology objectives during the PhD thesis:

1) Learn how no-shear, tensegrity structures can decrease mass with high stiffness in mechanical systems. Learn tools for building and then simulating the static and dynamic performance of these structures.
2) Explore and develop new design tools for creating stiff low-mass structures that are controllable with optical dimensional precision. Learn how to model and measure the optical and mechanical performance of these structures.
3) Design and build a 0.5m-scale low-mass tensegrity multi-aperture telescope for testing opto-mechanical performance.
4) Develop and test the necessary real-world tension actuators and sensors for controlling optical support structures.
5) Build a series of opto-mechanical structures of increasing diameter for laboratory measurements. Learn and use interferometric metrology techniques.
6) Create a 0.5m thin-mirror optical element and validate its use for optical telescopes.

Type of Research to be developed: (describe the observational, theoretical or instrumental content of the work to be developed by the PhD student)
This PhD thesis is mainly instrumental and requires the student to become familiar with the concepts of mechanics, optics, wavefront sensing, and their lab implementation. The student will work on design and mathematical formulation of the tensegrity structures that allow shape and shape control of precise optical surfaces and an overall optical support structure that are subject to slow gravitational and thermal influence. Specialized Python and finite element numerical models will be implemented. He/She will work on the experimental laboratory demonstration of these opto-mechanical systems. He/she will learn about all processes related to astronomical research, mathematical methods and may be required to learn about, for example, neural networks and their implementation in Python. He/she will also acquire valuable skills such as writing proposals and scientific papers and planning+performing experiments for astronomical instrumentation.

We also envision one or several long-term visits to collaborating institutions like the University of California San Diego (collaborator Mauricio de Oliveira), Dynamic Intelligent Systems in Vancouver Canada (Ye Zhou and his team), the MorphOptic Laboratory in Hawaii, and other institutions participating in LIOM in order to broaden the vision and training of the student.

Project Summary:

Scientific background:

- Technology now exists, or is on the immediate horizon, that will enable large optical systems that are capable of resolving and measuring faint sources that are not accessible with current remote sensing instruments and detectors. The possibility of creating ground-based telescopes at the 35m-scale with sufficient wavefront control to both fully overcome the effects of the atmosphere, but with exquisite coronagraphic capability starting at the telescope entrance pupil, means we may solve some of the most fundamental cross-cutting scientific questions: like, “is there life outside of the solar system?” The creation of these optical systems will pull together broad research disciplines, novel optical systems, and including machine learning.

- Since the discovery of the first extrasolar planet orbiting a solar-type star, 51 Peg b (Mayor & Queloz 1995; Nobel prize of Physics 2019), the numbers of exoplanets has grown up tremendously. After several decades studying a large variety of exoplanetary systems, the main objective is now the detection and characterization of telluric exoplanets. One of the major discovery of the next decades would be the detection of biomarkers and exolife. This requires collecting images and spectra of planets that can be up to 10^9 times fainter than their host star. Such unprecedented contrast, angular resolution and spectral stability require several technological innovations and a novel telescope concept that LIOM is designing.
- New large telescope concepts is likely to replace stiff mass with pre-tensioned cables (also known as tensegrity) as well as lighter active optical control systems. The ExoLife Finder **(ELF)** telescope depends on using active wavefront control technologies to decrease the mass and cost of a 35m-scale telescope by an order of magnitude or more. Developing novel solutions for decreasing the mass of the mirror payload in these instruments is important. ELF uses sub-aperture off-axis telescope units in a Fizeau interferometry optical configuration where the light of all sub-apertures is brought to a common coherent focus. The optomechanical concepts developed in this research program will advance the technical readiness of an ELF telescope.
- The **Small-ELF** telescope is a 4m-scale 15 sub-aperture Fizeau telescope that is now being built on Teide mountain in the Canary Islands by the IAC as a prototype for ELF. It will test tensegrity concepts, Fizeau imaging, and Machine Learning and Mach Zehnder wavefront measurement technologies.
- **Micro-ELF** is a laboratory 0.5m version of a tensegrity telescope with 5 sub-apertures that will be used for developing and testing the creation and performance of a tensegrity low mass optical system.
- **Why tensegrity is important?** The low mass and high stiffness of a tensegrity system practically enables large increases in telescope size and photometric dynamic range performance derived from the opto-mechanical improvements in wavefront fidelity. With laboratory tensegrity experiments we will devise and test necessary opto-mechanics sensors and actuators that allow us to improve our models of the ultimate performance of large Fizeau optical systems. These opto-mechanics are also key for optical space applications, especially in the rapidly expanding space optical communication community.

Key steps: Learning and testing new algorithms for geometric form-finding and modeling of tensegrity structures. Real-world laboratory testing of the mechanical nodes in these theoretical structures. Detailed designs of useful optical surface support and overall tensegrity optical payload support. Measuring performance and extrapolating to high-fidelity ELF and space optics performance models.

Scientific objectives of the PhD:

- **Identify** the requirements, strengths, and weaknesses of various new technologies for creating lightweight opto-mechanical systems.
- **Demonstrate and devise activation, metrology and control techniques** For shape control of mm-scale thickness small optics and large overall optical payloads
- **Create** and measure the performance of precise, low-mass tensegrity optomechanical elements

Schedule: (The project needs to be carried out in three years)
We emphasise that reading literature about adaptive optics, wavefront sensing, optical metrology and optics creation should be conducted continuously during the length of the PhD thesis. Reading will be more intense at the beginning but should continue during the PhD to remain up-to-date with discoveries by other groups.

Below is a tentative time frame for the different phases of the PhD:
Year 1: semester 1: Read papers to get knowledge on the subject of tensegrity systems. Learn Prof. Oliviera's numerical modeling tools for thin mirror support.
Year 1: semester 1: Learn to use optical interferometry metrology tools and swing arm mechanical metrology tools.
Year 1: semester 2: Extend the design of idealized tensegrity structures to include real actuators and sensors. Learn and explore control concepts for thin mirror and active tensegrity structure design.

Year 2: semester 1: Construct Micro-ELF tensegrity telescope structure.
Year 2: semester 2: Measure opto-mechanical performance and refine structure

Year 3: semester 1: Construct and measure 20cm-scale thin mirror support structure
Year 3: semester 2: Write the resulting papers and the PhD thesis.

Supervisor's experience on the research subject:

Prof. Jeff Kuhn is a professor at the University of Hawaii Institute for Astronomy and Chair of the ERA LIOM program. He's been the PI or coI for nearly $300M of experimental research grants and contracts and has supervised graduate students for approximately 35 years in a range of instrumental, observational, and calculational astrophysical problems. He is fully devoted to the educational goals of advancing graduate research with LIOM. His role in co-advising the PhD will be to provide optics-metrology domain expertise, general research guidance, and to be a bridge to collaborators (Dr. Ye Zhou and Prof. de Oliveira) who have advanced mechanical and control system discipline knowledge. Kuhn will be deeply involved in this thesis as it is related to some priority tasks of the LIOM program. We note that Prof. Kuhn will be in residence at IAC and IACTEC approximately every other month and in direct contact with the thesis student. Prof. Kuhn will be the primary advisor for activities related to this thesis.

Dr Patricia Fernandez has more than 19 years of work experience in engineering, 3 of them in construction projects as a Civil and Production Engineer and the last 16 years as a Mechanical Engineer at the Instituto de Astrofísica de Canarias (IAC), in the design, AIV and commissioning of Mechanical, Optomechanical, Cryogenic and Vacuum Systems for astronomical instrumentation. She has experience in the development of simulation programs during my doctoral thesis, the design, manufacture and testing of opto-mechanical prototypes in the LISA Laboratory (Laboratory of Imaging and Sensors for Astronomy) and my experience in the development of astronomical instrumentation (OSIRIS, EMIR, HARMONI, GranCain, Quijote), which are key aspects in the development of this thesis.

Dr. Ye Zhou: Dr. Zhou is the past president and chief engineer of Dynamic Structures Ltd. (Vancouver Canada) and the founder and CEO of Dynamic Intelligent Structures, Ltd. He is a world leader in using tensegrity structures in telescope design. His companies have designed some of the largest telescope components in the world, including Keck, TMT, and CFHT. Email: yeezhou@gmail.com