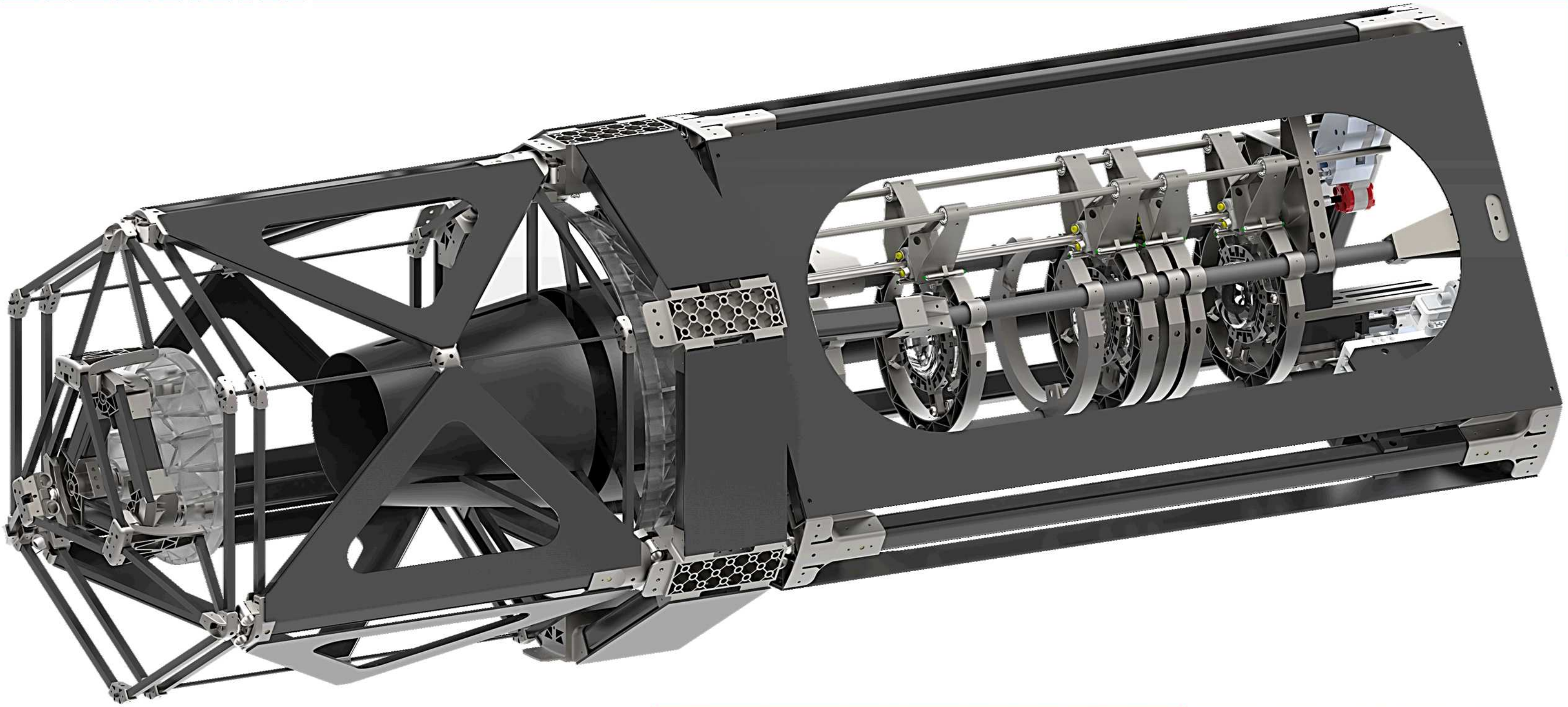
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2019-5056C

Design and Build of a Zoom Telescope Utilizing Manufacturing



PRESENTED BY

Ted Winrow – Sandia National Laboratories

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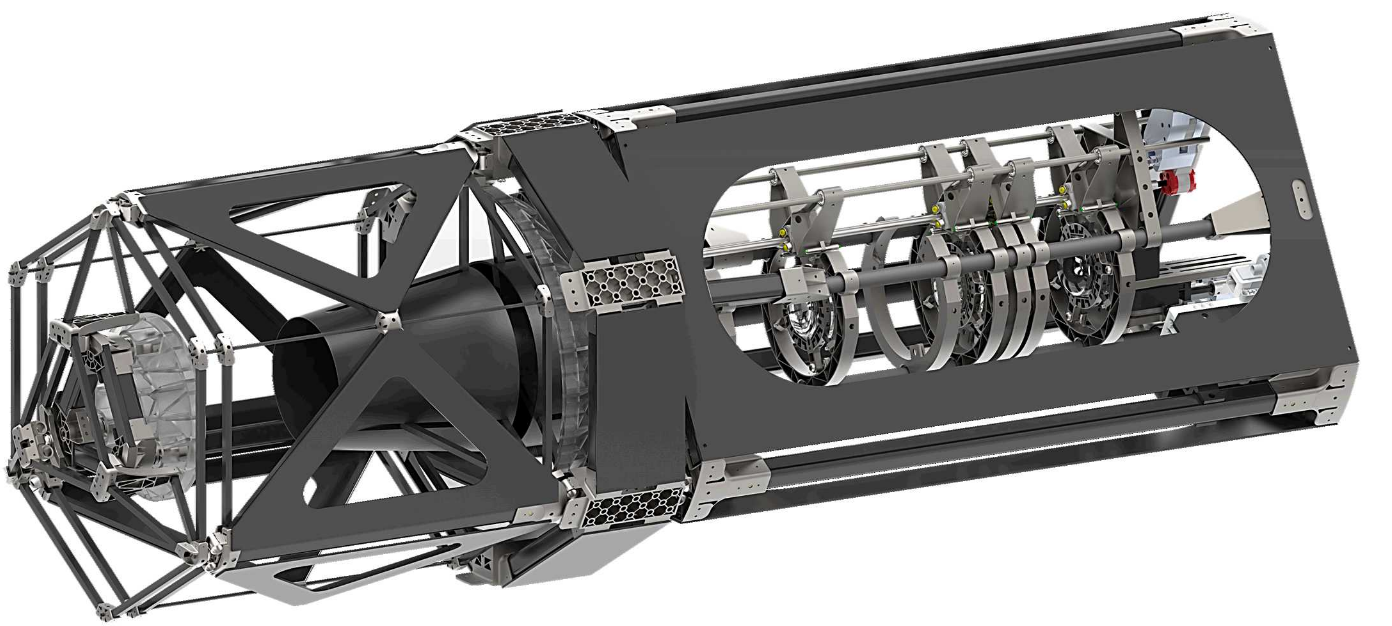
Xoom Project Overview

Sandia National Labs Directed Research, technology demonstration project from October 2013 – October 2016

Purpose: To design, build and test a precision, lightweight imaging system at a fraction of the time and cost of equivalent systems today

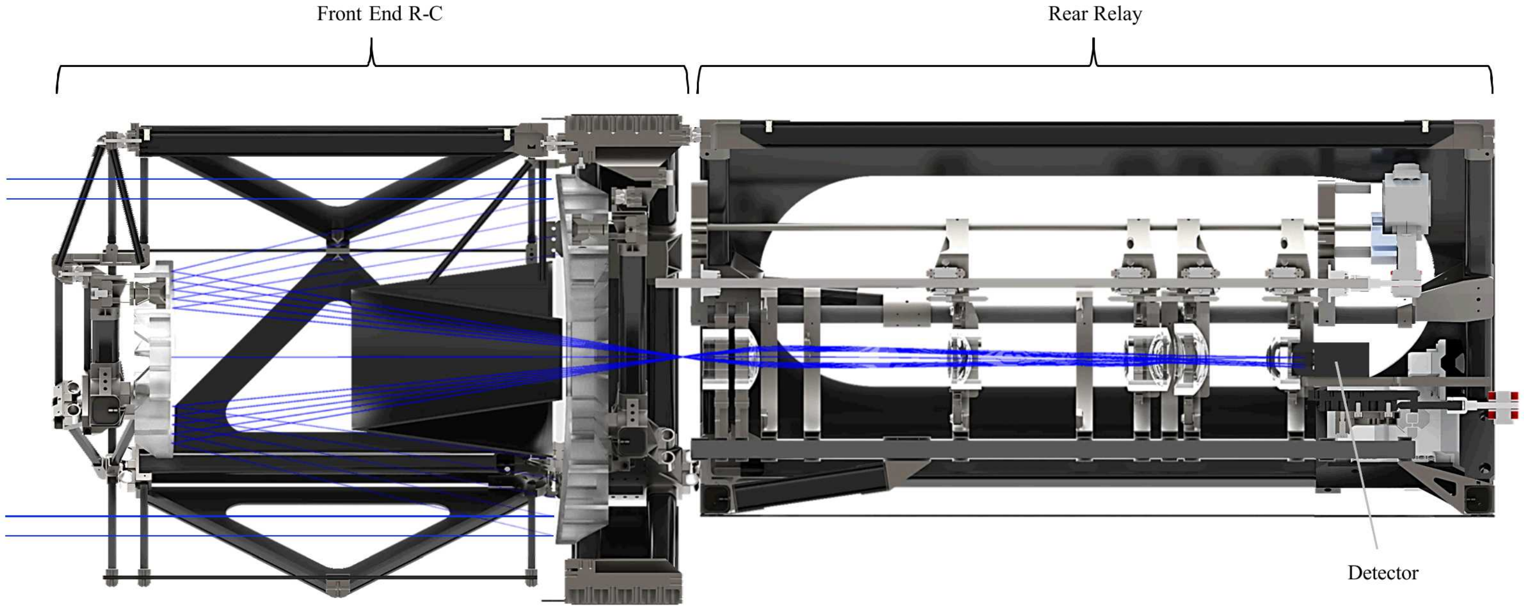
Goals
- Incorporate a 10x discrete zoom capability
- Utilize additive manufacturing (AM) technologies
- Lightweight, athermal design
- Incorporate image correction algorithms and expected correction benefits into the optical design merit functions

This presentation's focus: Opto-mechanical design for additive manufacturing
- Fabrication assumptions
- Optical alignment methods and tools
- Not discussing optical design, optical fabrication, motion system, image correction algorithms



Xoom Technical Team – Sandia National Laboratories
- Ted Winrow – Project Lead, Opto-mechanical Design, Analysis, and Alignment
- Jeffery Hunt – Optical Design, Analysis, and Alignment
- Victor Chavez – Mechanical Engineering
- Jessica Pehr – Mechanical Engineering
- Zachary Kreiner – Mechanical Engineering
- Eric Shields – Optical Processing
- Dennis Lee – Optical Processing

Optical Design Baseline

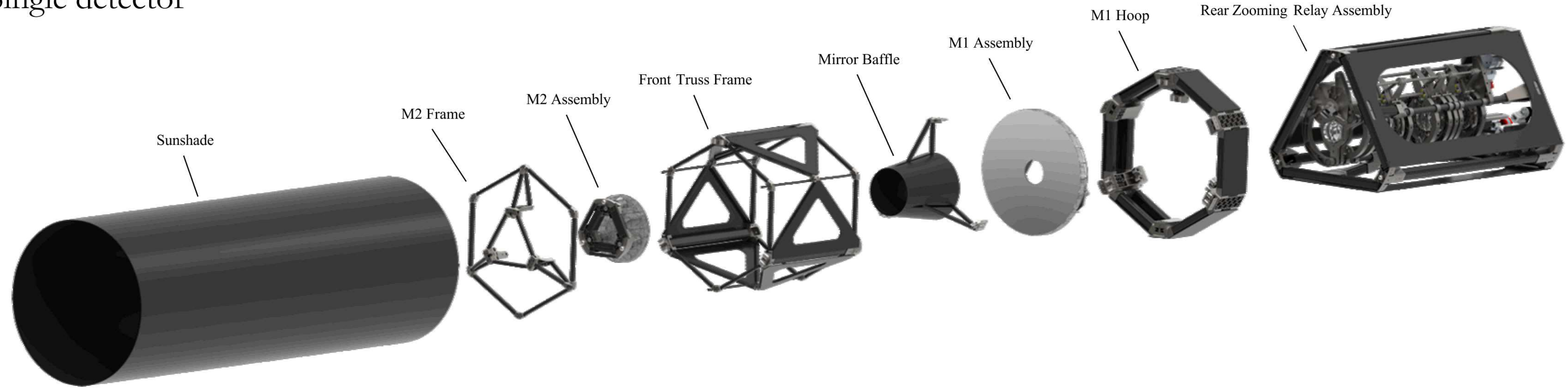


Ritchey-Chrétien front end telescope

- 12 inch diameter primary mirror (304.8mm)
- f/3 R-C system

Refractive relay behind

- 10x, discrete zoom (image performance only at 2 positions, wide and zoomed)
- Single detector

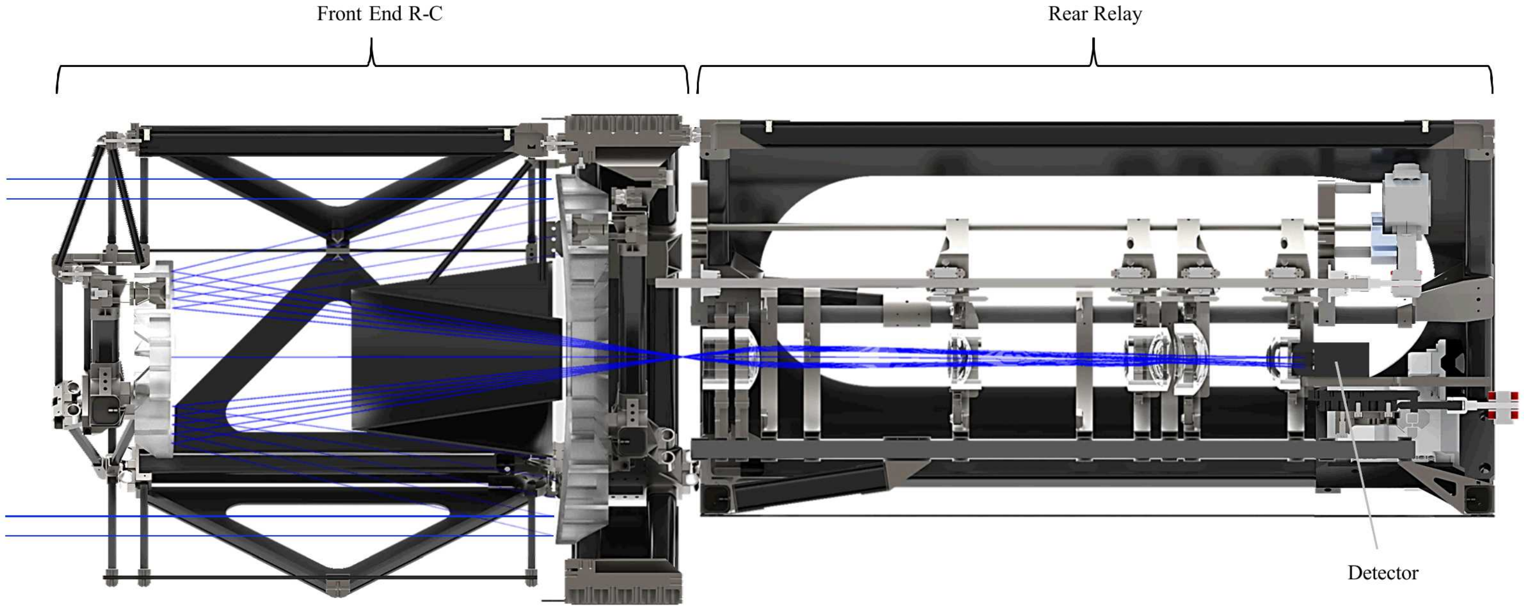


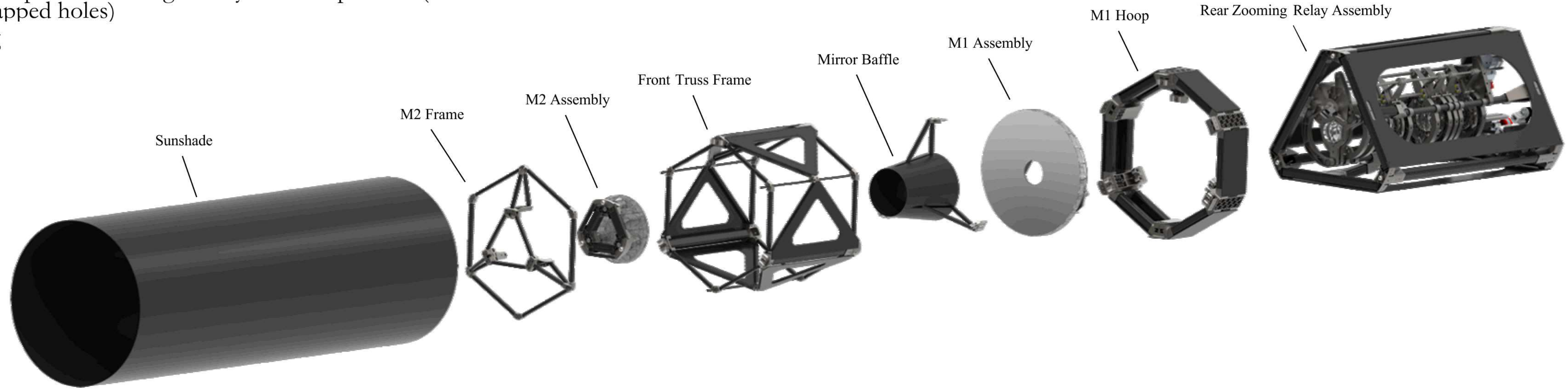
Opto-Mechanical Design Baseline

Active alignment of all optics, bonded with epoxy
- Autocollimator/Air Bearing Alignment Station
- Hexapod positioners
- Allows for low-precision, low cost, but stable structures

Carbon fiber, truss-based structure with titanium AM connectors
- Low CTE carbon fiber and titanium connectors create thermally stable structure
- Easily manufactured components

Focus on speed for design-through-fabrication
- All custom metal and plastic components to be AM parts
- No post-machining on any AM components (besides tapped holes)
- N





Active Alignment

Dynamically positioning an optic using real-time feedback

Feedback: metrology/position

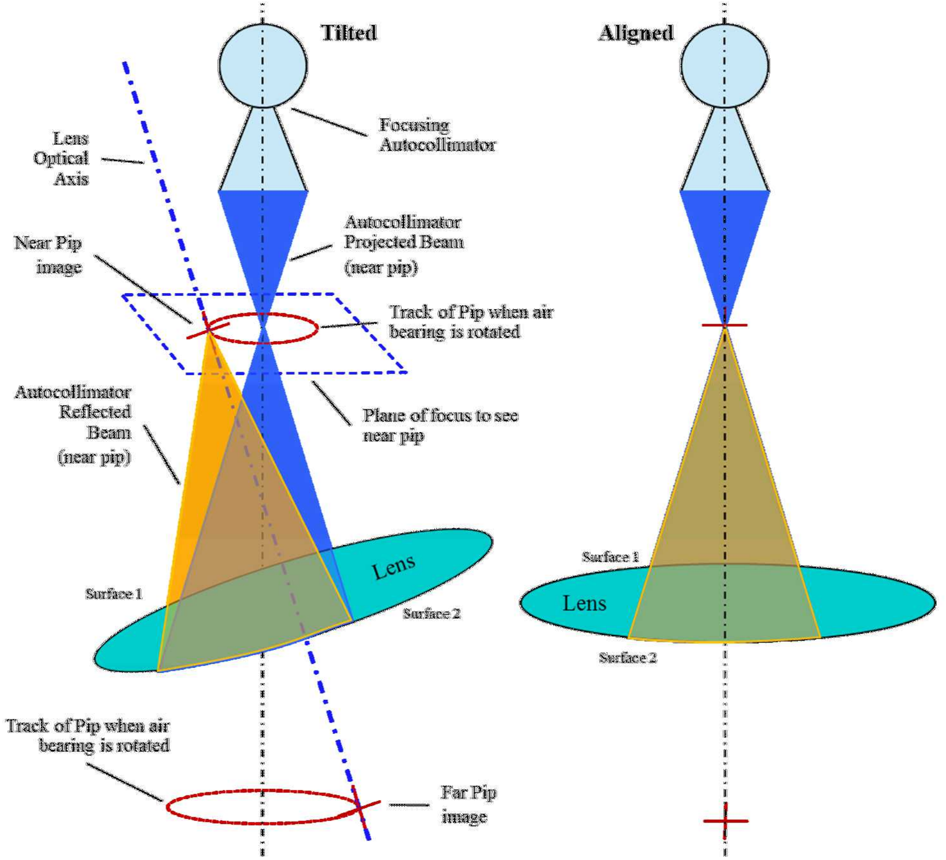
- Optic's optical axis distance error from a common, stable reference such as an air-bearing axis or an autocollimator axis
  - View the "pip" return from a focusing autocollimator aligned to the center of curvature of each optical element surface
  - 2 pips per optic, positions define the optical axis in space
- Through-system image performance (for primary mirror)

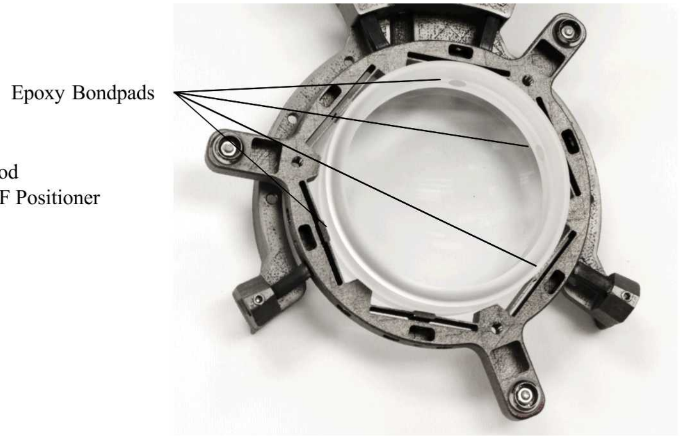
Motion

- Six degree of freedom, precision (1 micron) hexapods with programmable pivot point to reduce cross-talk

Lockdown

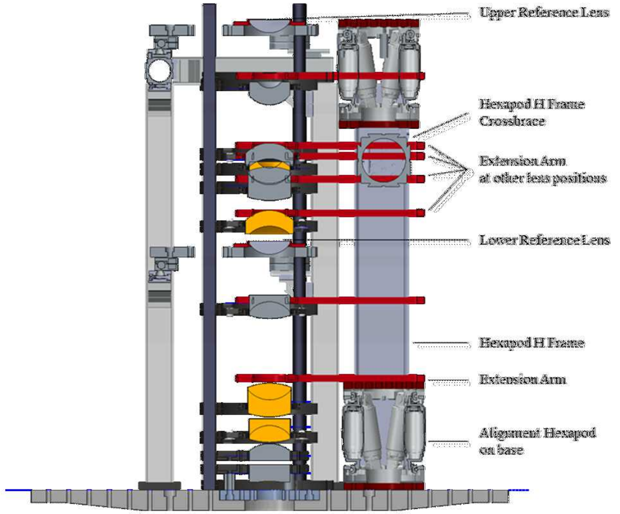
- Masterbond EP21TCHT-1 epoxy
  - 2 part, room cure
  - Highly filled, low CTE, thick like toothpaste

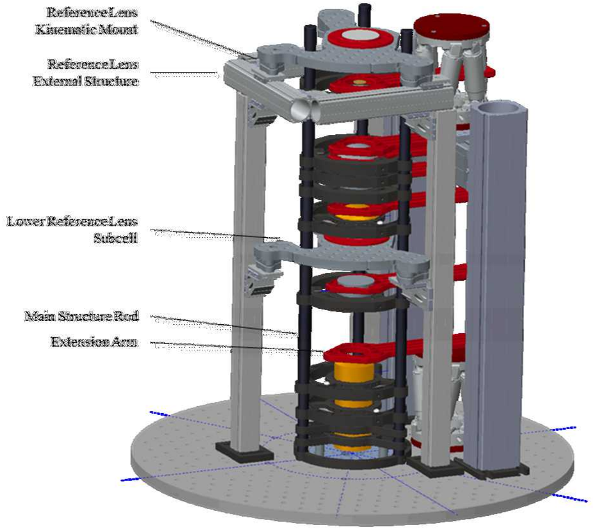


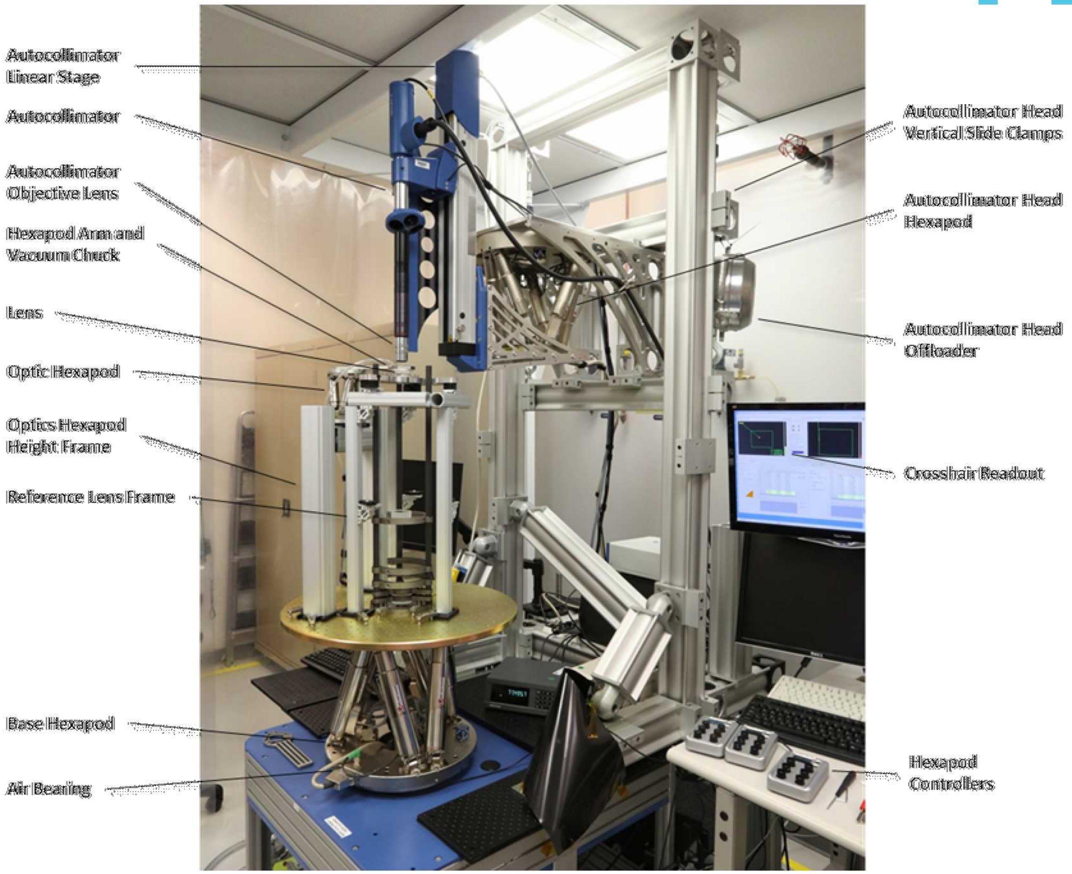


Active Alignment Tools for Rear Relay Optics

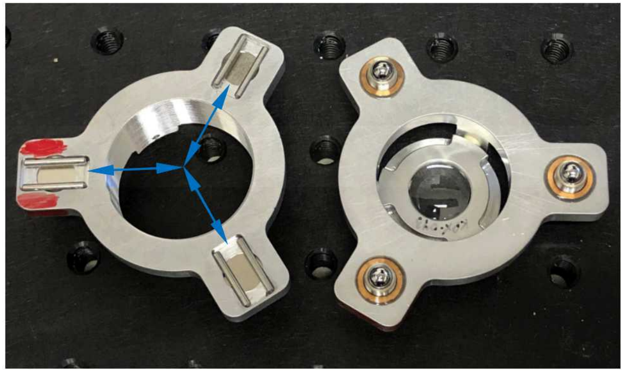
- Metrology Feedback - pip location relative to air-bearing axis
- “Master” reference optic bonded first
  - Mounted on a repeatable kinematic mount above all system lenses so it can be installed and measured at any time during the build
  - Check for structure drift overnight, bumps, etc.
  - Stable piston reference
- Large lower, base hexapod aligns master reference and system structure to air bearing
- Small hexapod aligns current optic to the air bearing and holds during epoxy cure
- Lenses bonded sequentially from bottom to top



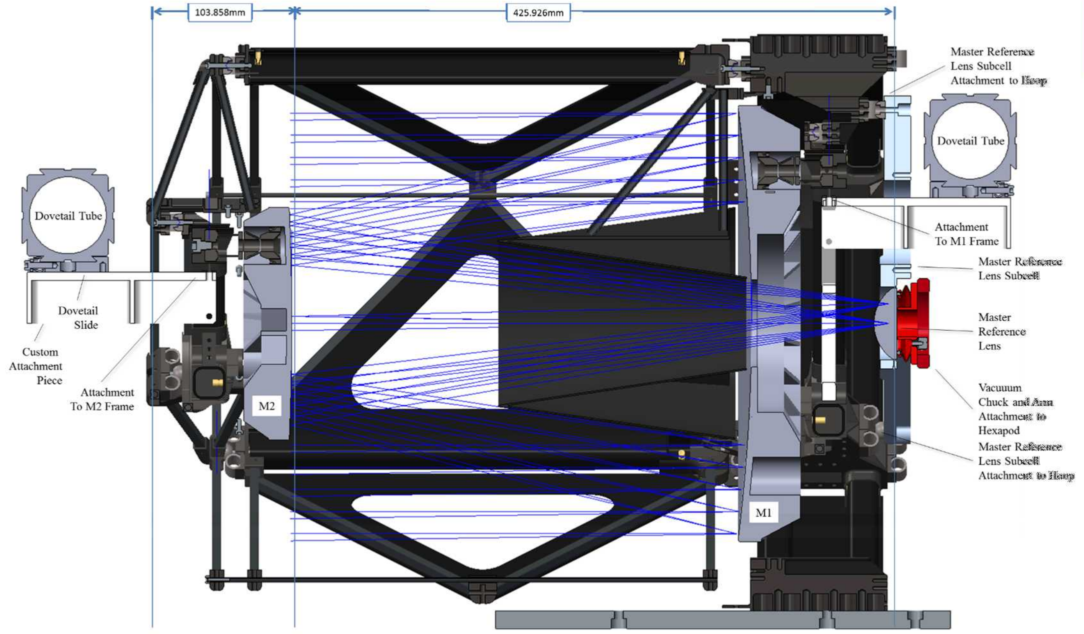




Kinematic Mount Example
3 Balls fit into 3 Vs
Center of Vs creates thermal expansion center



Active Alignment Tools for R-C Front End

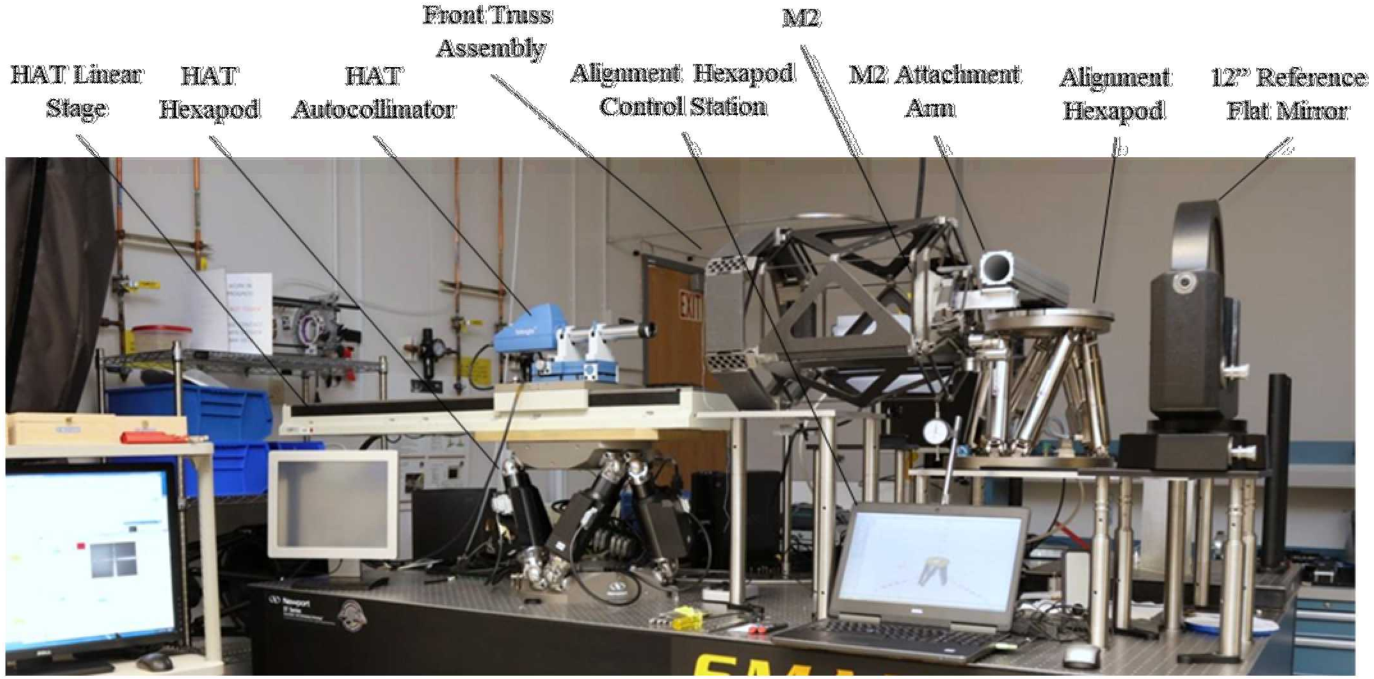


Horizontal Autocollimator Tool (HAT)

- Focusing autocollimator mounted to precision linear stage, all on 6 DOF hexapod for alignment to reference optics.
- Pips measured against autocollimator axis (no air bearing)
- Custom tool calibrated to compensate for sag of linear stage at various autocollimator positions
    - Creates a stable, virtual autocollimator axis even though autocollimator travels on an imperfect stage

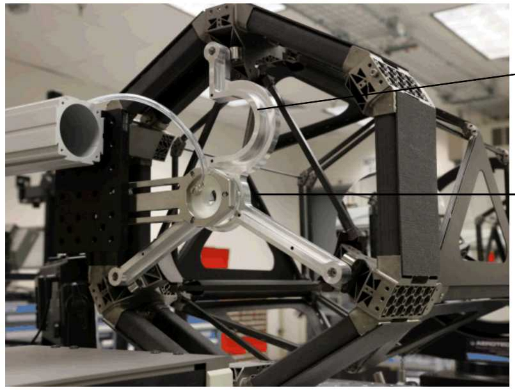
Alignment

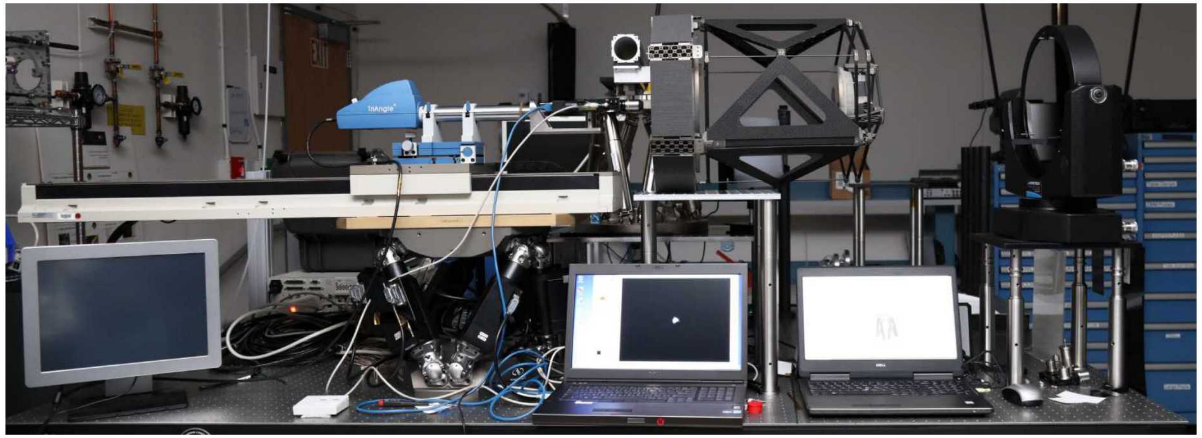
- "Master Reference Lens" placed at R-C prime focus
- M2 aligned and bonded using pip return and fiducial at mirror vertex (on surface)



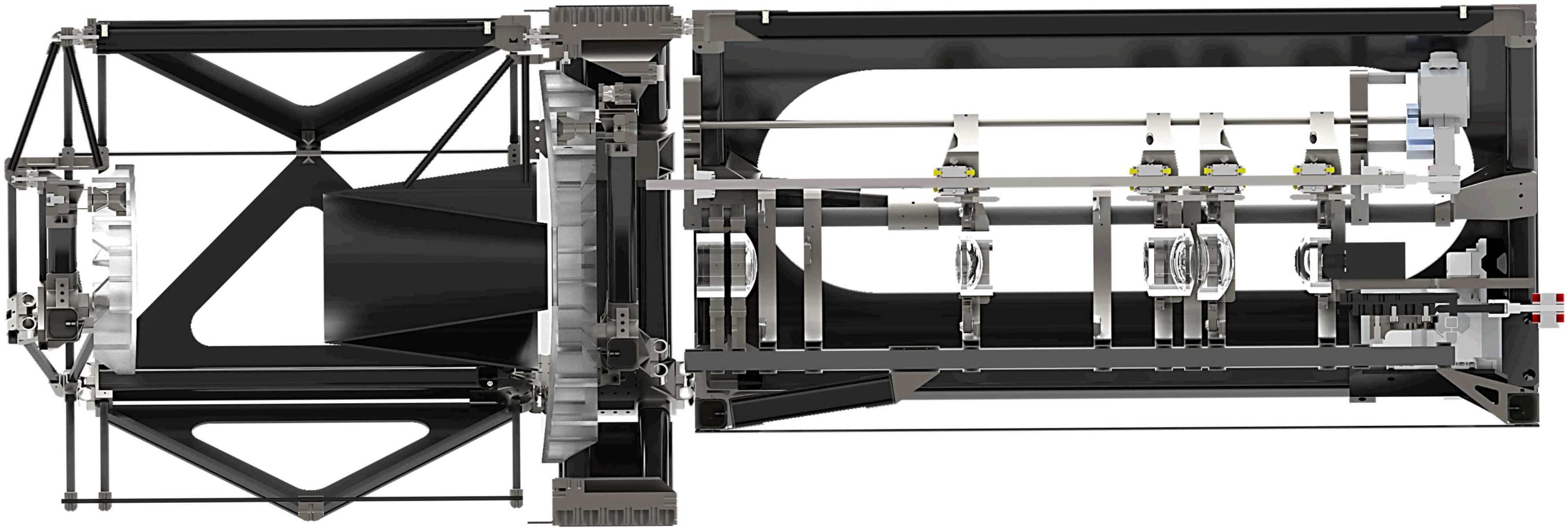
Active Alignment Tools for R-C Front End (continued)

- Point Source Microscope (PSM) added for primary mirror alignment (M1)
  - PSM attached to autocollimator on linear stage and focused at prime focus location
  - M1 on alignment hexapod and free to move
  - Double pass test, M1 positioned to minimize spot size and irregularity





Opto – Mechanical Design



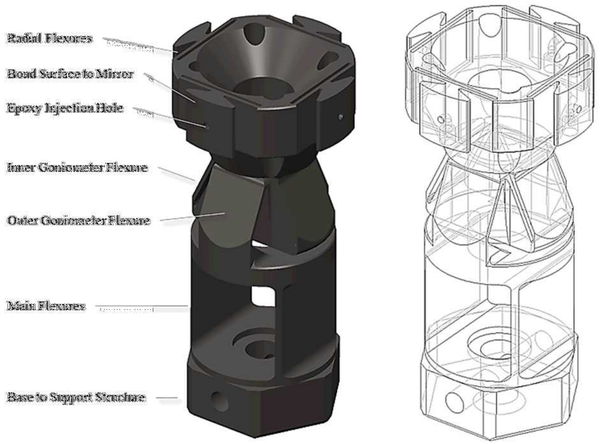
Reduce Thermally Induced Stress and Misalignment

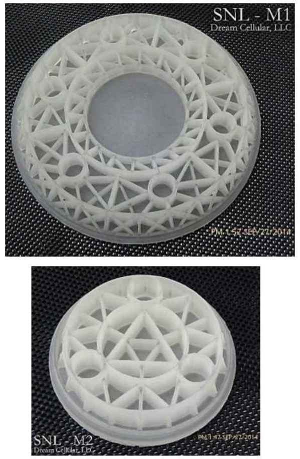
Choose materials with relatively close thermal expansion coefficients (CTE)

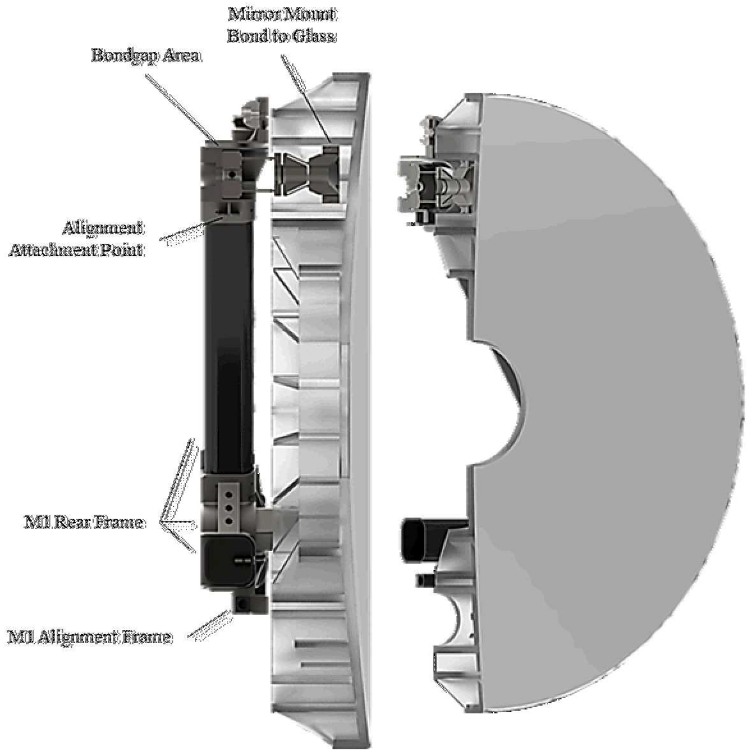
- Mirrors – Pyrex
- Flexures, metal parts – Titanium 6AL-4V
- Carbon Fiber
- Low CTE epoxy

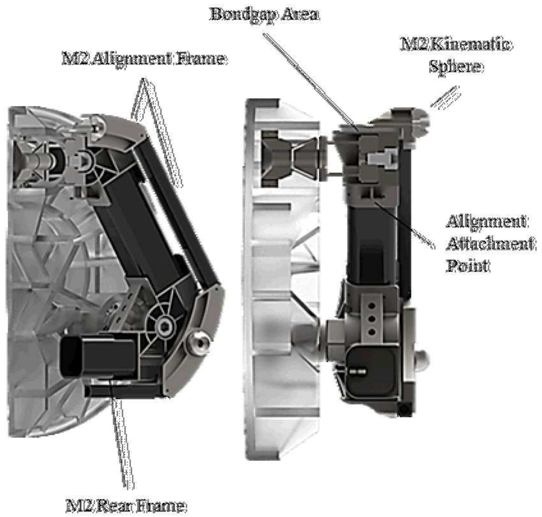
Design flexured, near-kinematic interfaces for critical attachments

- Patented monolithic, flexured mirror mount
- 3 mounts with radial flexibility accommodate differential thermal growth without misaglinment
  - Defines thermal expansion center at center of mirror
- Goniometric flexures reduce moment loads into mirror which can cause distortion





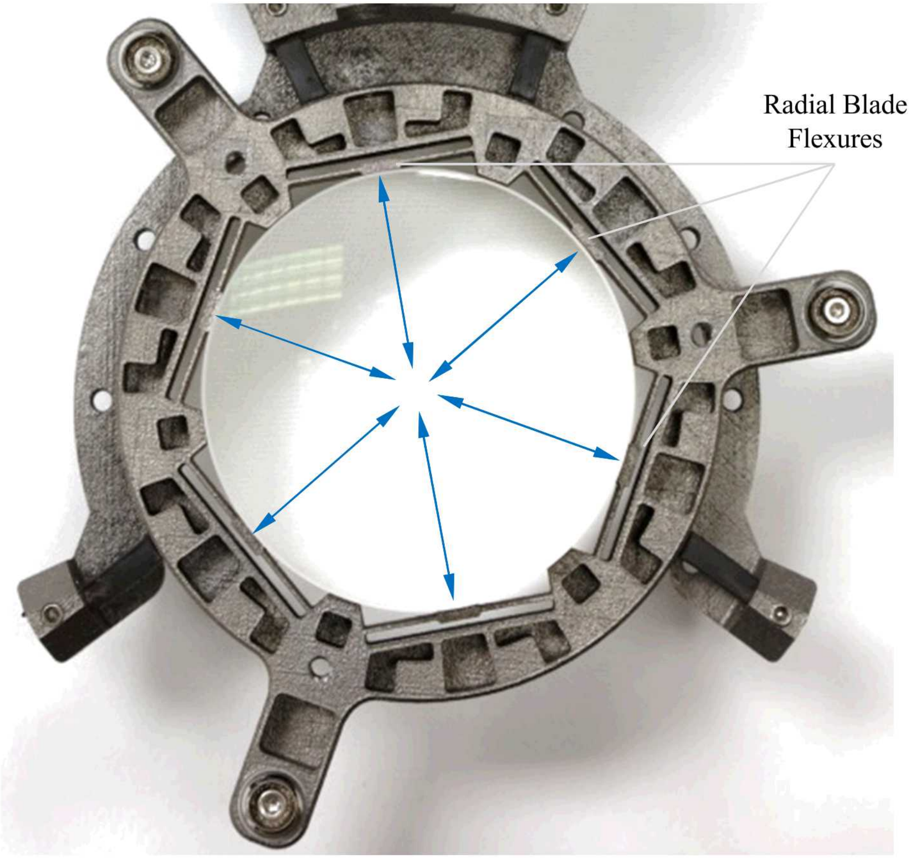


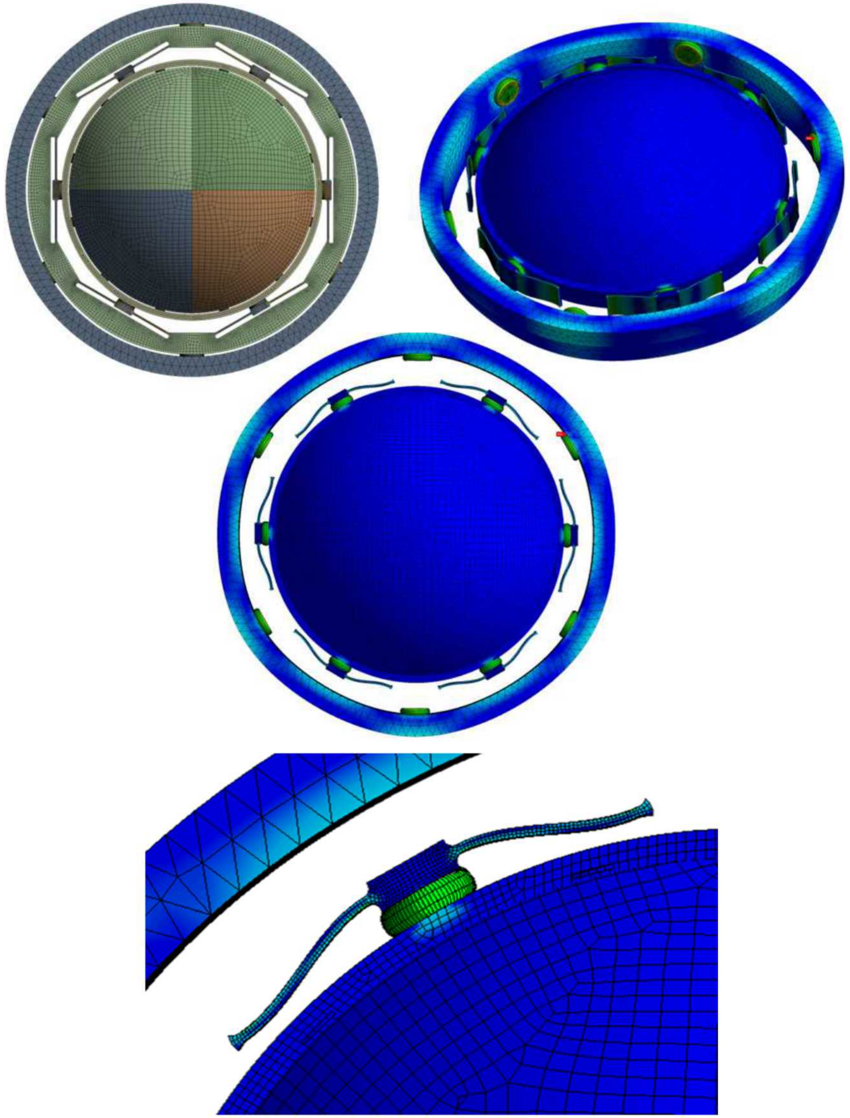


Reduce Thermally Induced Stress and Misalignment (continued)

Radial flexure sets for lenses

- Maintains alignment and reduces stress during temperature swings
- Thin metal blade flexes out easily but is very stiff in all other directions except rotation about the pad
- Series of blades prevents rotation about any one pad
- Series of blades only allows expansion about center of lens



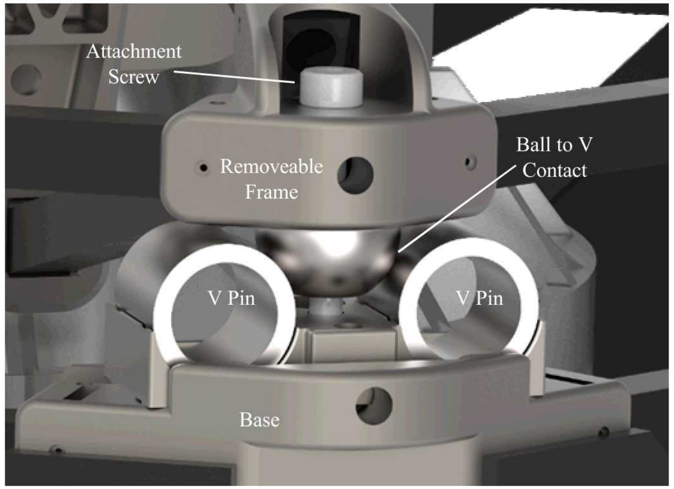


Radial Blade Flexure Example: Finite Element Analysis Showing Deformed Shape at Temperature (200x actual displacement)

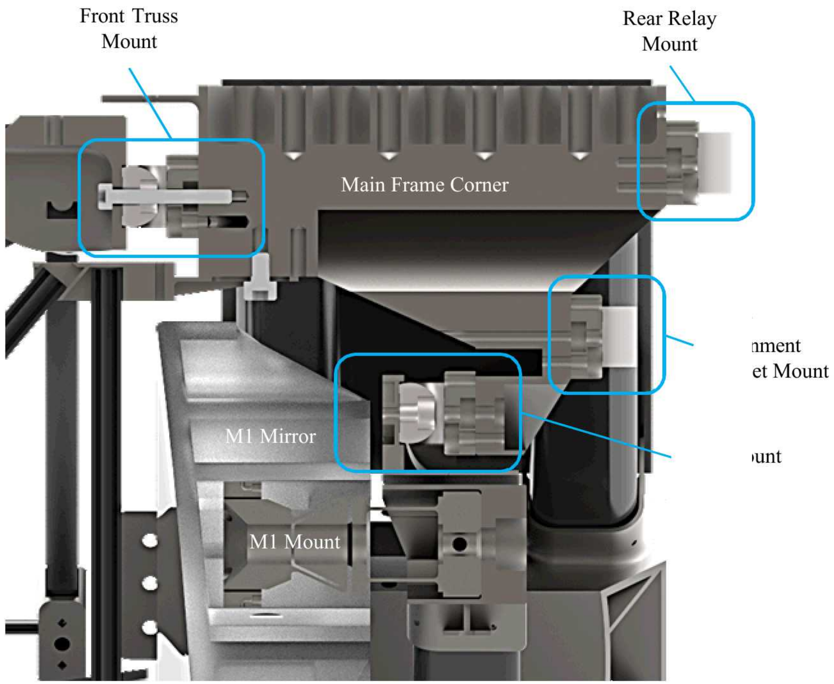
Reduce Thermally Induced Stress and Misalignment (continued)

Kinematic Attachments

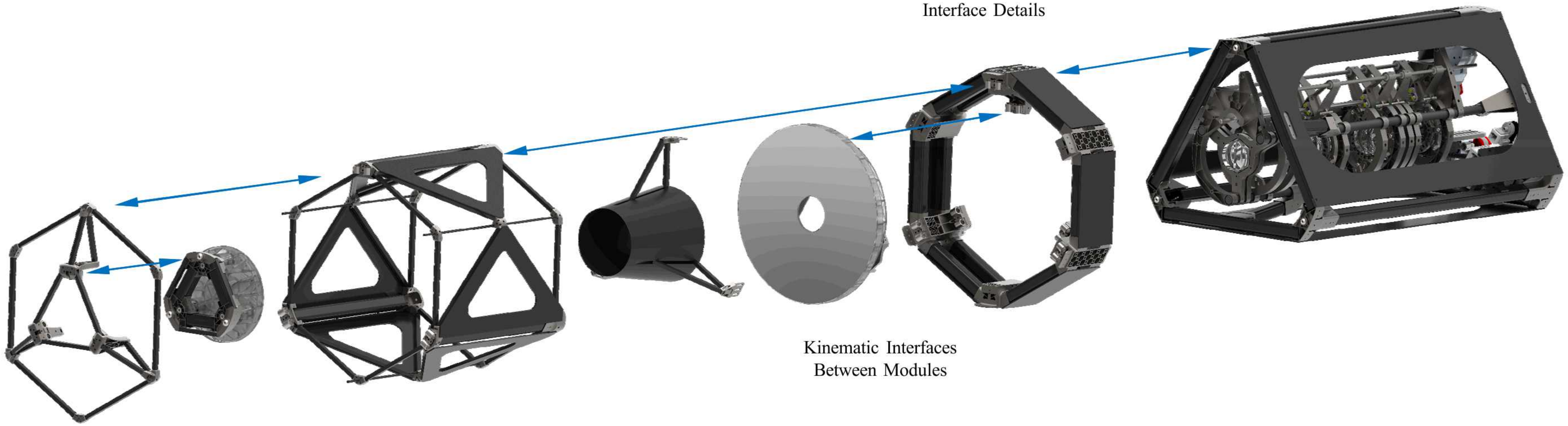
- Separates major telescope modules
- 6 DOF 6 Constraints
- Ball-in-V design allows radial compliance
- Allows repeatable assembly/disassembly for transport and testing
- Prevent attachment stress from non-precision interfaces



Kinematic Interface



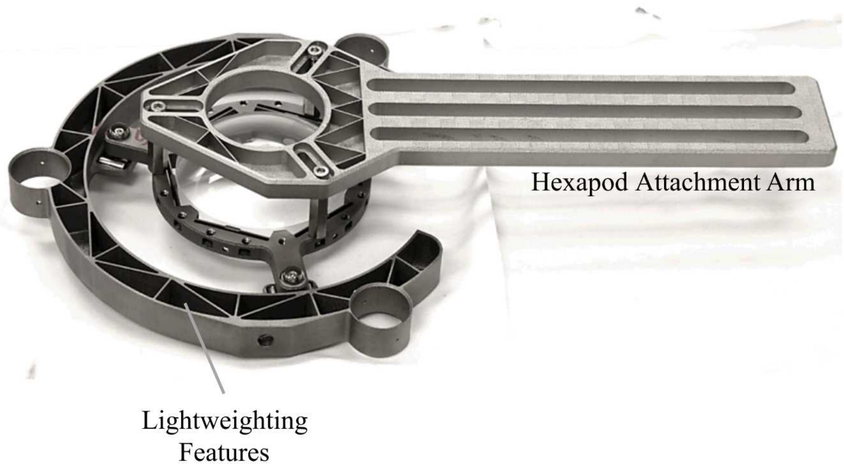
Main Frame Kinematic Interface Details

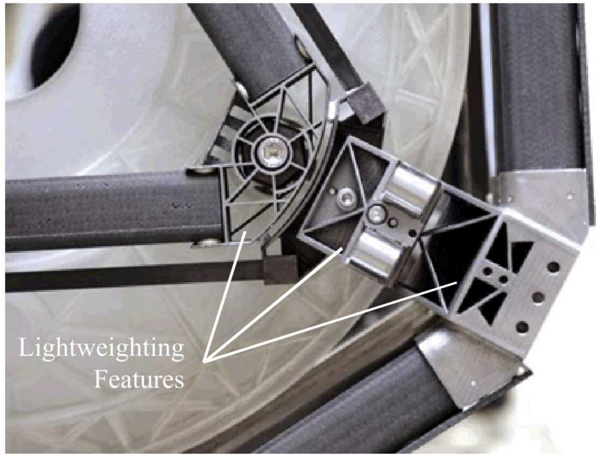


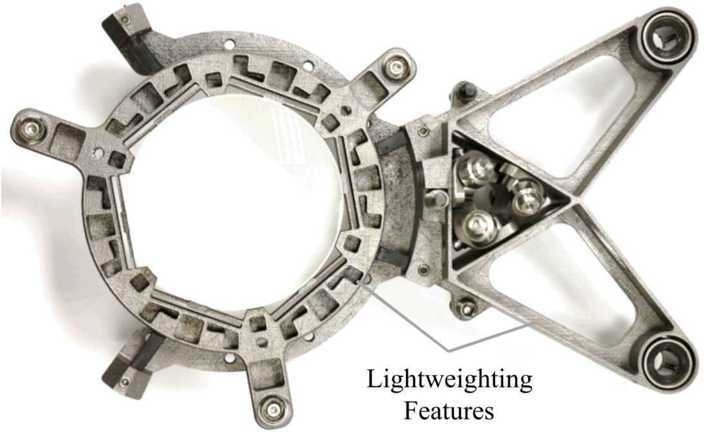
Kinematic Interfaces Between Modules

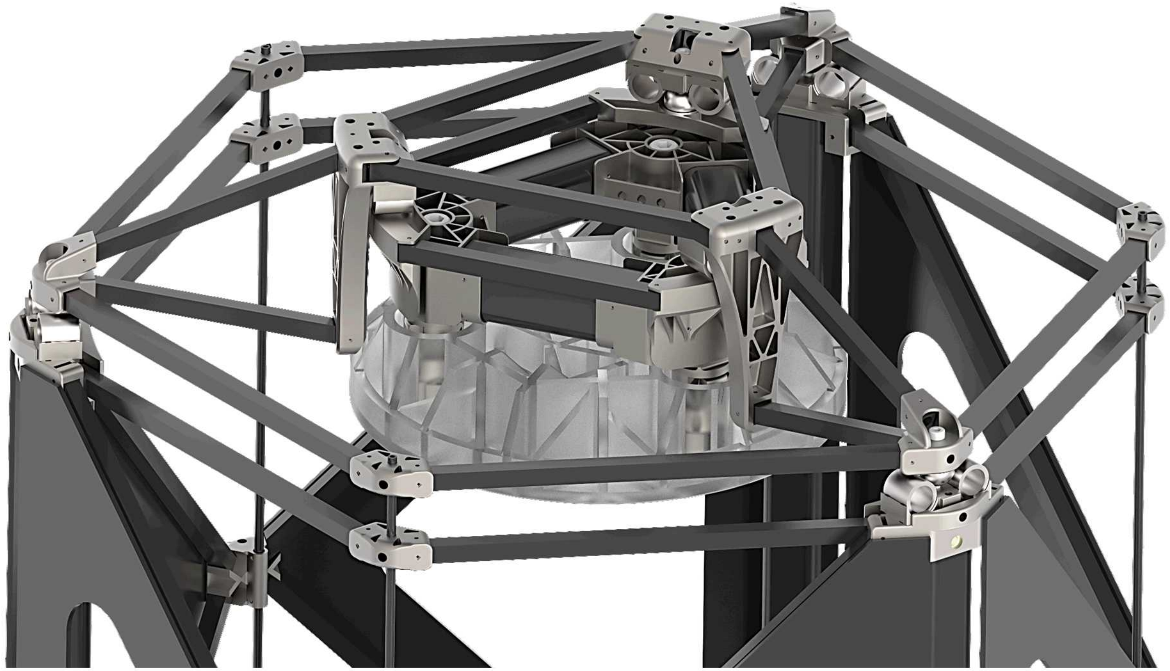
Lightweight and Stiff Design

- Carbon fiber where possible (black parts)
- Thin walled, large cross section round and square tubes for high stiffness to weight ratio.
- Titanium components extremely lightweighted
  - Targeted 1mm thick walls and ribs wherever possible
- Structural epoxy attachments bonded on multiple planes
  - Create geometry where epoxy has to fail in compression for as many orientations as possible
  - Shifts failure mode from adhesion failure to bulk material failure (stronger, less variable)



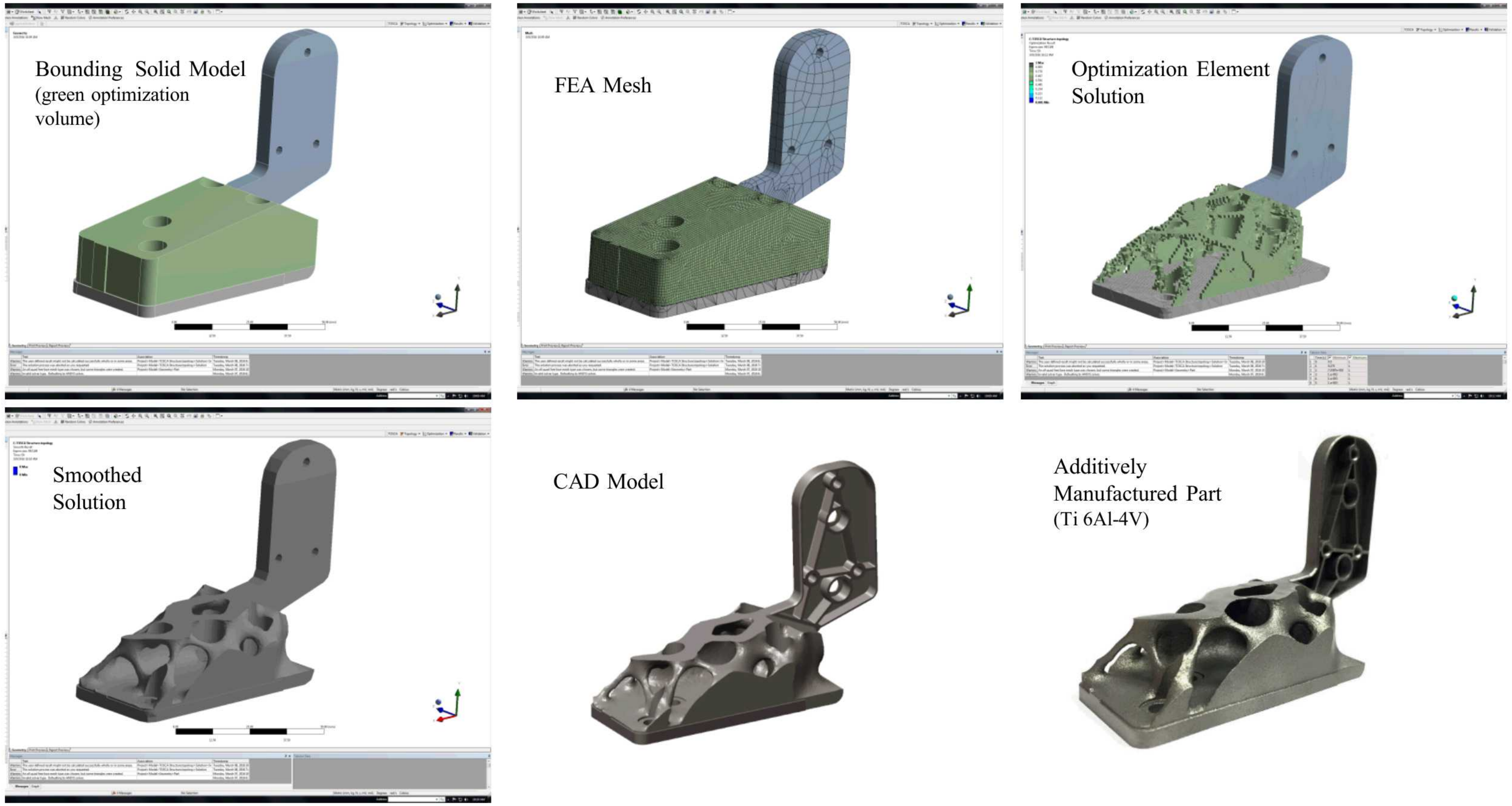




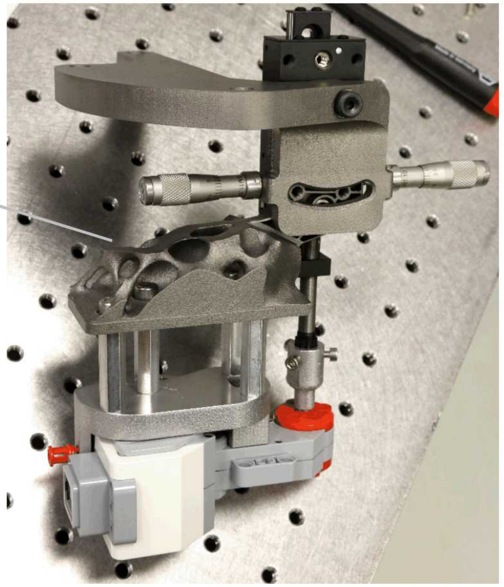


Topological Optimization

- Ansys® 14 with Tosca® plugin (2016)
  - Many usability enhancements since that time
- Computationally expensive for optimization solution
- Labor intensive
  - FEA solution transfer to usable CAD geometry
  - Software dependent
  - Improving with software updates
- Useful in non-intuitive/complex loading conditions
- Useful for extreme lightweighting needs



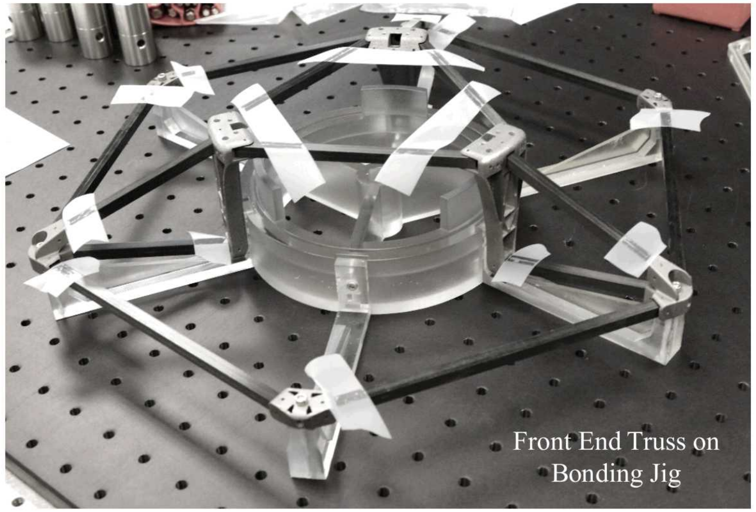
Assembled
Bracket



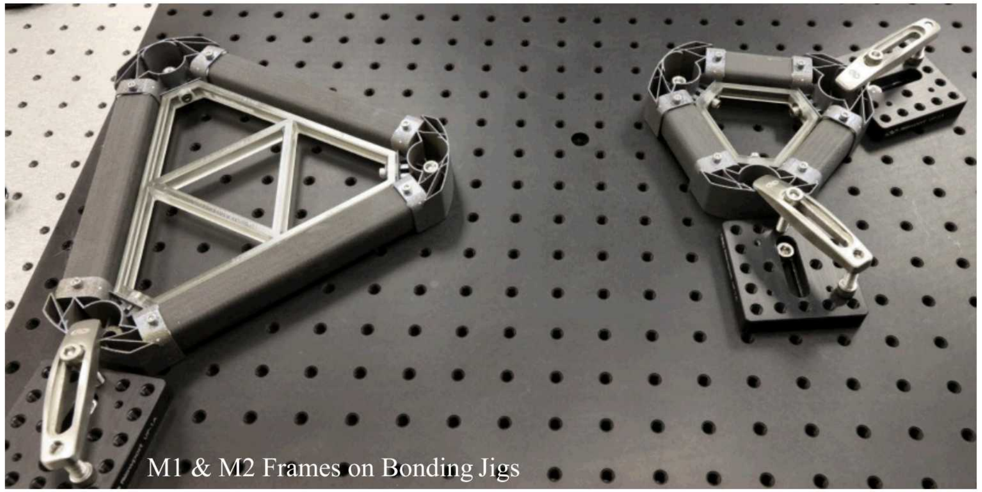
Design For Assembly

Extensive use of bonding jigs and fixtures

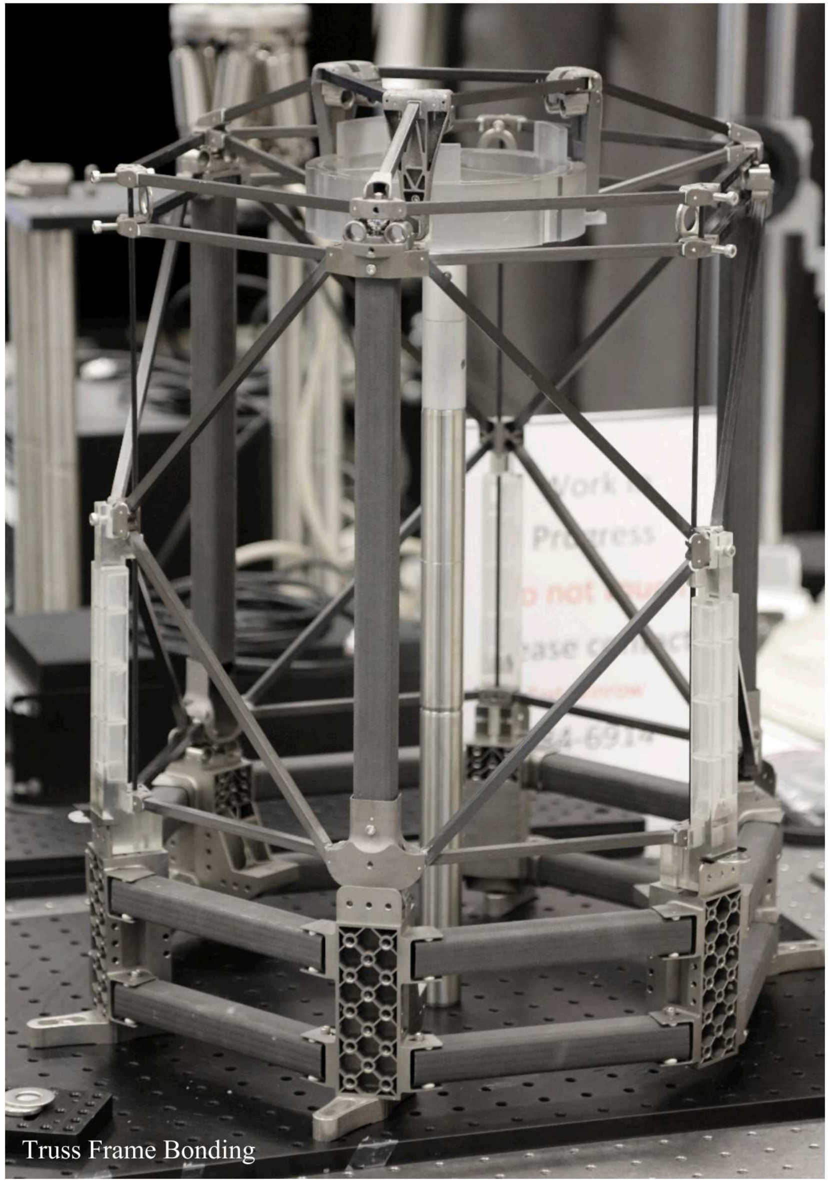
- Positions an holds components during epoxy cure
- Additively manufactured plastic components
- Modular bonding jig assemblies for use during multiple assembly phases



Front End Truss on Bonding Jig



M1 & M2 Frames on Bonding Jigs



Truss Frame Bonding

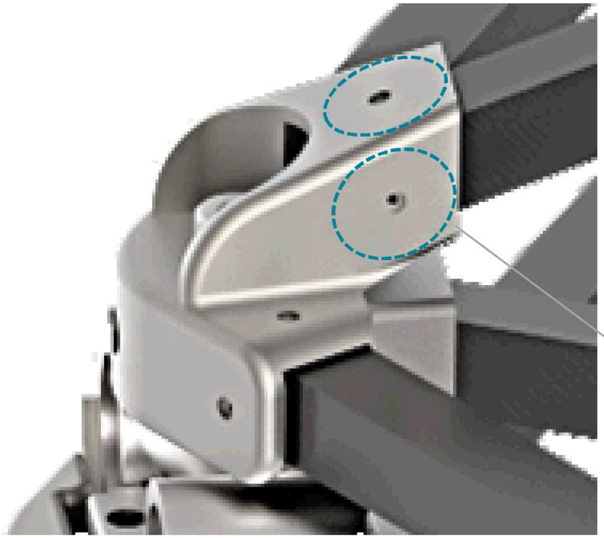
Design For Assembly (continued)

Designed registration features

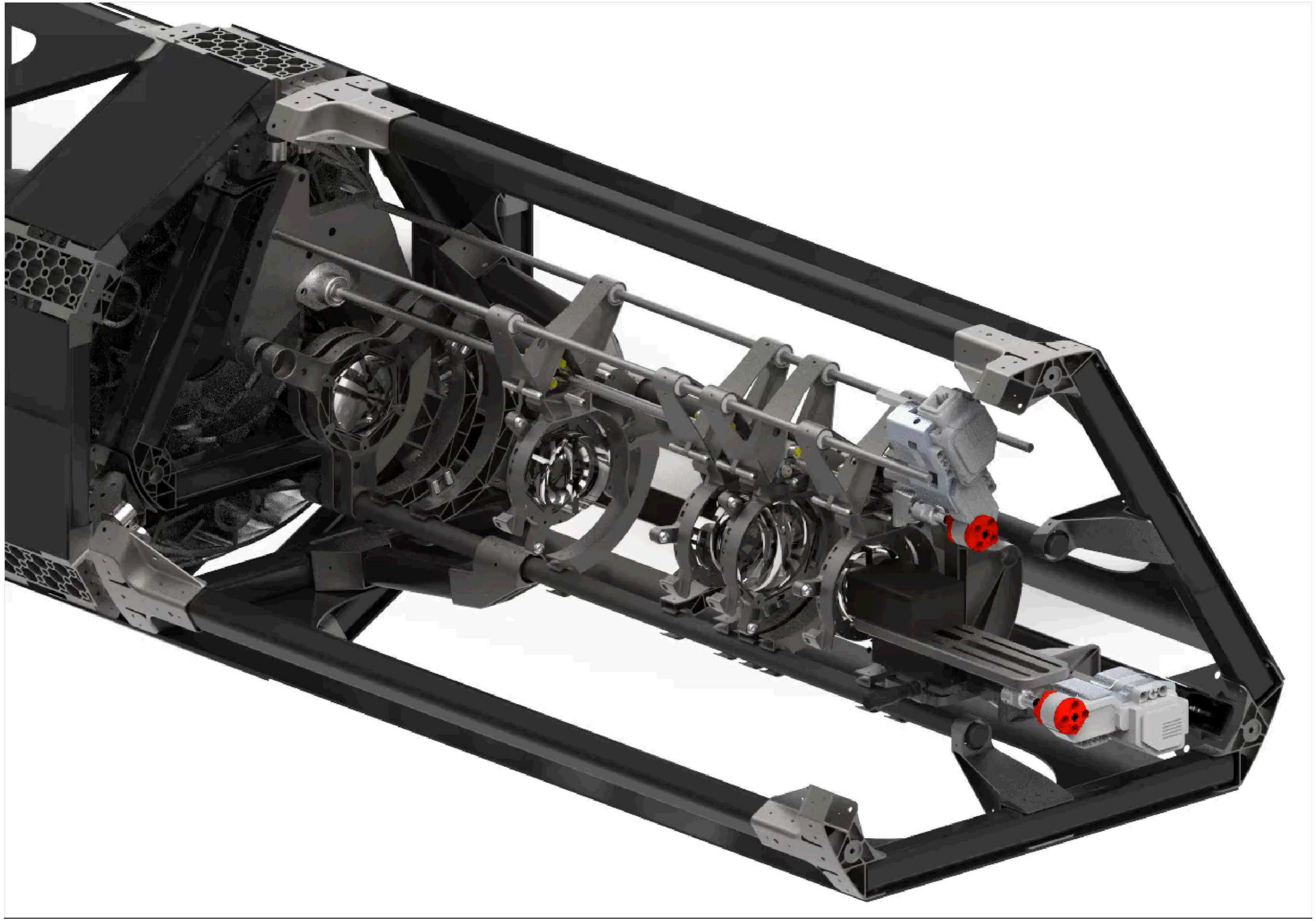
- Slots for square tubes to provide rough alignment and epoxy attachment surfaces

Epoxy management features

- Injection holes in AM components, some curved
- Naturally occurring circular bondpads do not require edge cleanup
- Visible features to denote size of bondpads and when to stop injecting epoxy



Lens Motion



Rear Relay

Lens Motion

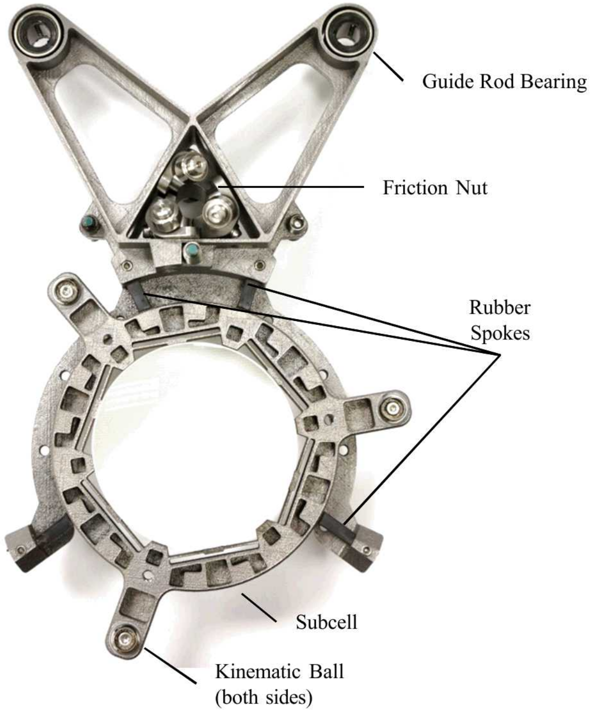
- Drive on smooth shaft with friction nuts
  - Multiple pitch travel on single drive shaft
  - Allows slippage if driven past stopping point (no damage)
- Lens subcell held by flexible rubber arms to friction nut carrier frame
- Subcells mount kinematically at each end of travel (wide angle and zoom positions) to fixed frames
  - Kinematic mounts use horizontally magnetized pins.
  - Rubber arms on carrier allow small motions to align to kinematic mount
- Fixed frames actively aligned and bonded with lens subcells attached

Motor Mechanisms

- Lego Mindstorms geared stepper motors
  - Lens Drive and Focus drive
  - Battery operated, multi-motor customizable system
  - Easily programmable
  - Remote control
  - Compact and inexpensive

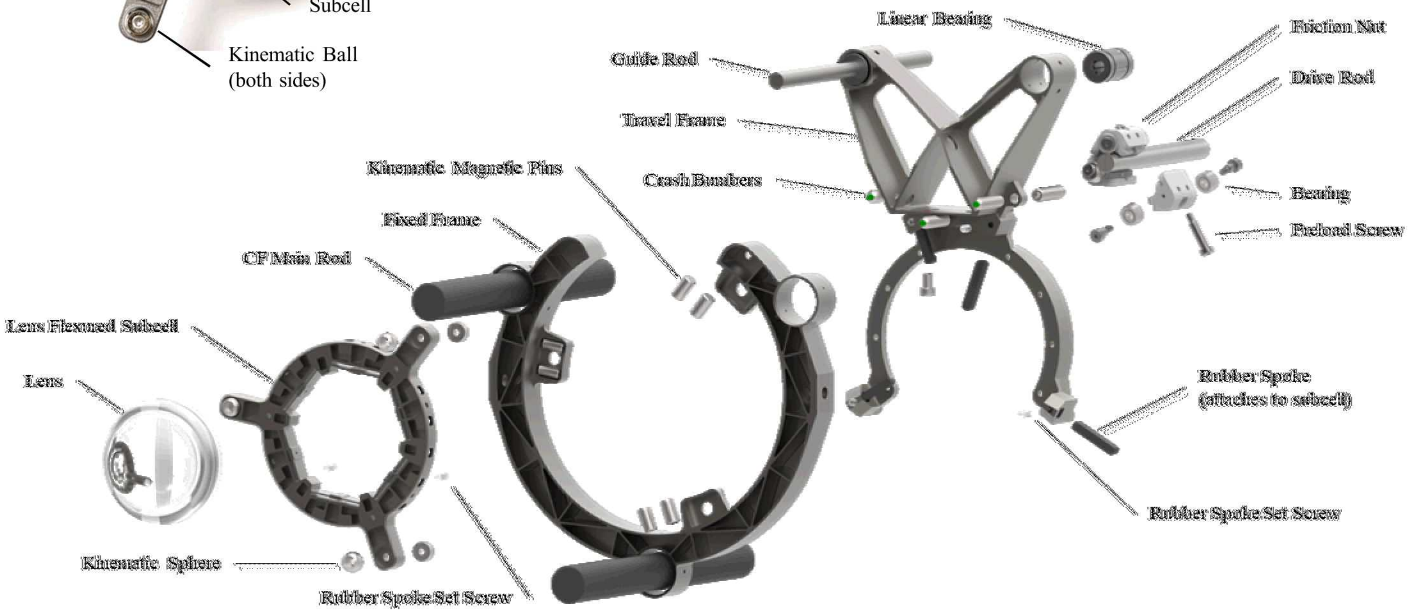
Relay Assembly Attachment

- Entire assembly actively aligned to R-C front section and bonded to triangular frame




Friction Nuts


Fixed Frame Bonding



Completed Assembly Notes

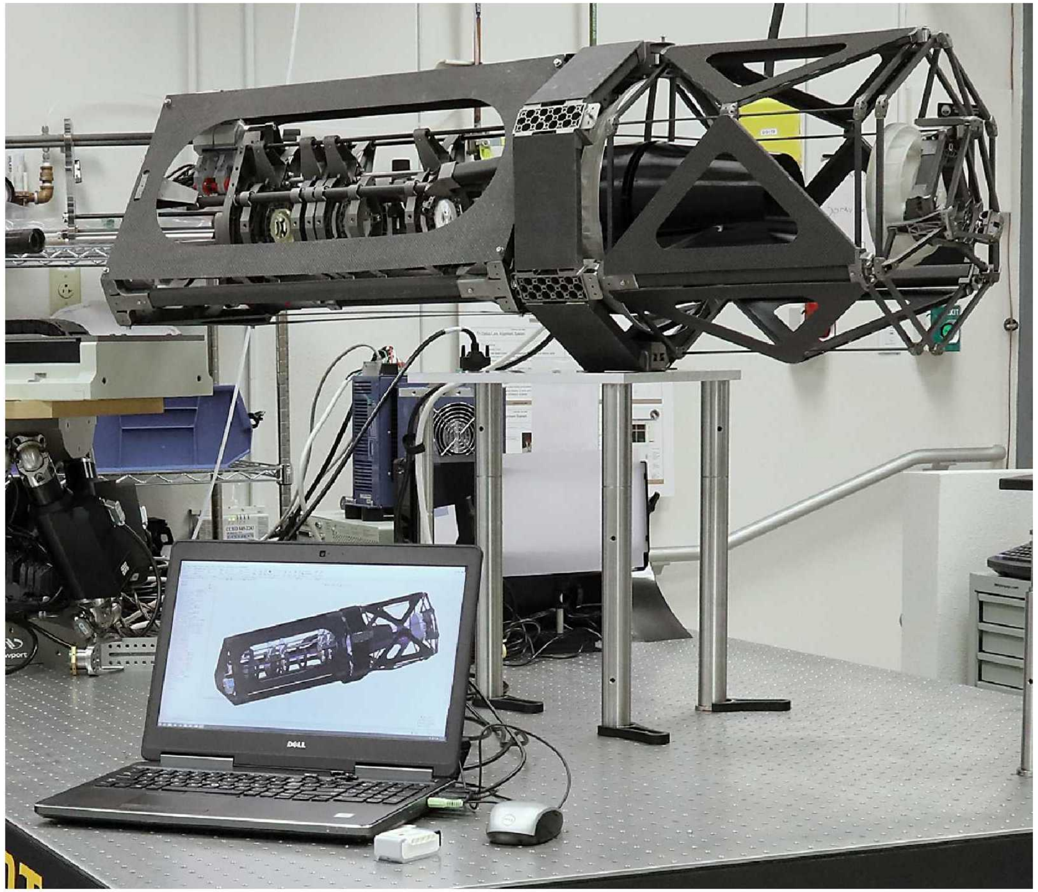
Mirror polishing cut short due to schedule
- Sub par image performance

Optics alignment results
- Fixed optics:
  - 12 microns decenter, 10 arcsec tip/tilt, 5 microns piston
- Magnetic attachment to fixed frames
  - Showed increased tip/tilt drift on epoxy cure
  - ~20-150 arcsec
  - Load path from hexapod to epoxy went through magnetic attachment interface which was insufficiently stiff

Mass
- Total System: 37.9 lb (17.2 kg),
- Front R-C module: 17.6 lb (8.0 kg)
- Commercial "lightweight",carbon fiber, f/8 R-C, 12" below weighs 52 lb (23.6 kg).


Commercial Carbon Fiber R-C Telescope


Fixed Frame Bonding



Field Testing

Outdoor testing in Albuquerque, NM
- July, 2016
- ~6000 ft elevation
- Imaging dominated by turbulence
- Commercial 2048x2048 color CMOS sensor

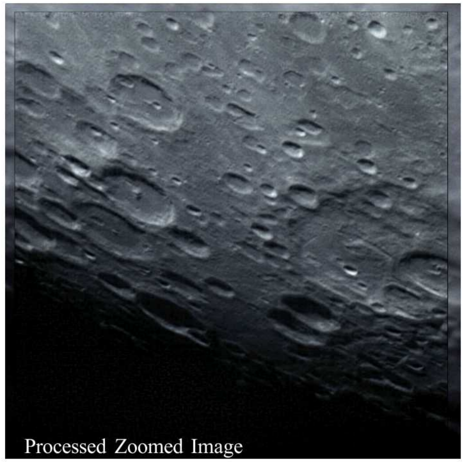
Data Processing
- DxO® software
  - Batch correction for color and contrast
- ATCOM® software
  - "Lucky imaging" and bispectrum image correction for turbulence, jitter and aberrations
  - 82Hz video, 50-image stacks

Imaging Results
- Raw images were as expected with primary mirror aberrations and turbulence effects
- Processed images showed much improvement

Timeline
- Opto-mechanical design start (excluding mirrors): September, 2015
- Opto-mech design through testing: 11 months

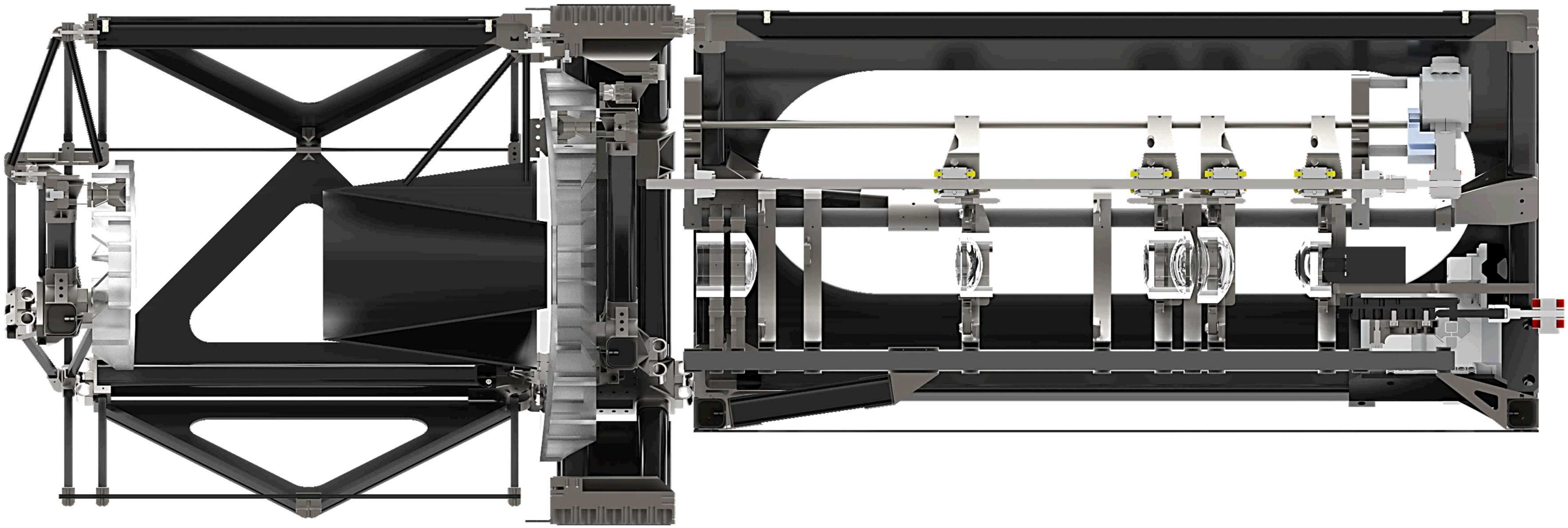
Raw image sample

Processed Wide Angle Image

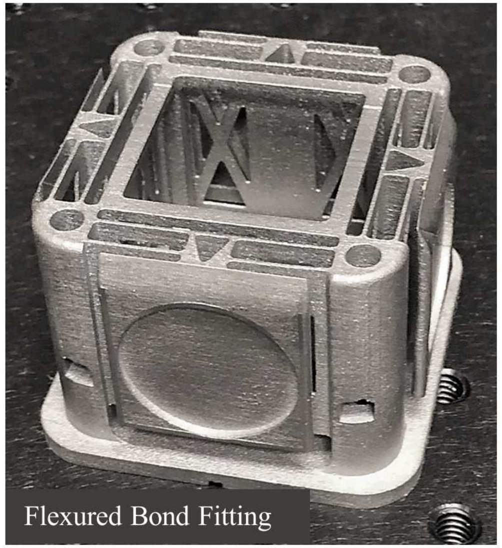


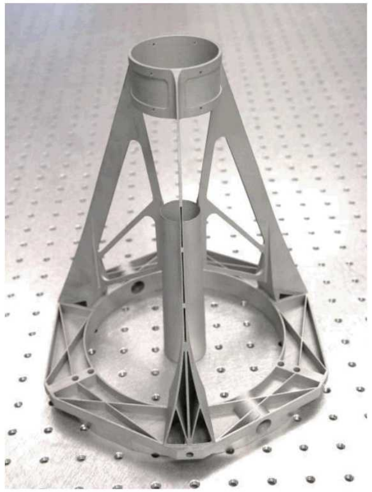
Processed Zoomed Image

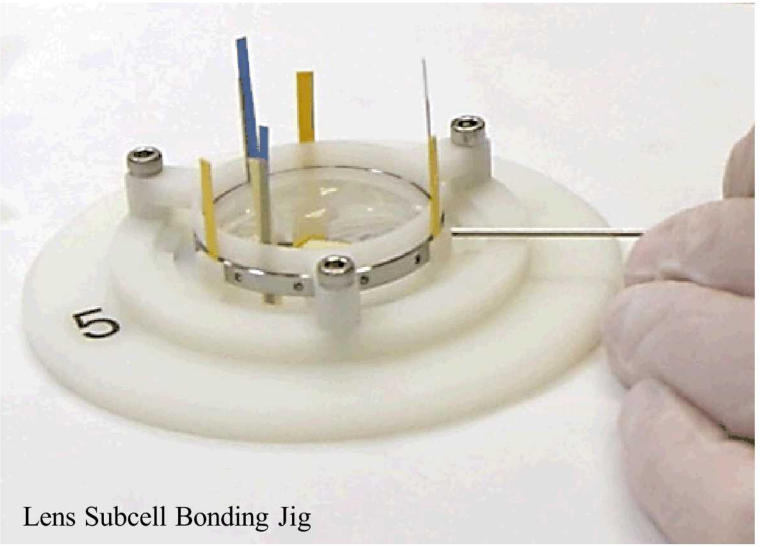
Additional Work



Additively Manufactured Components


Flexured Bond Fitting

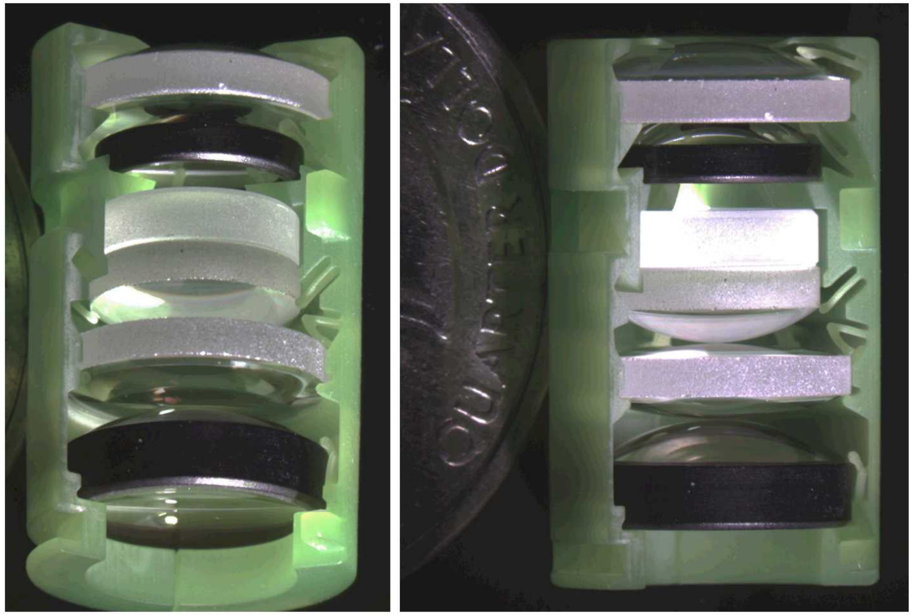

Monolithic Telescope Frame



Lens Subcell Bonding Jig

Small-Scale Lens Housing

- Rapid design/fabrication
- Integrated, discrete flexure retainers for each lens element
- 3 Housing segments snap together for fast, adhesive-free assembly

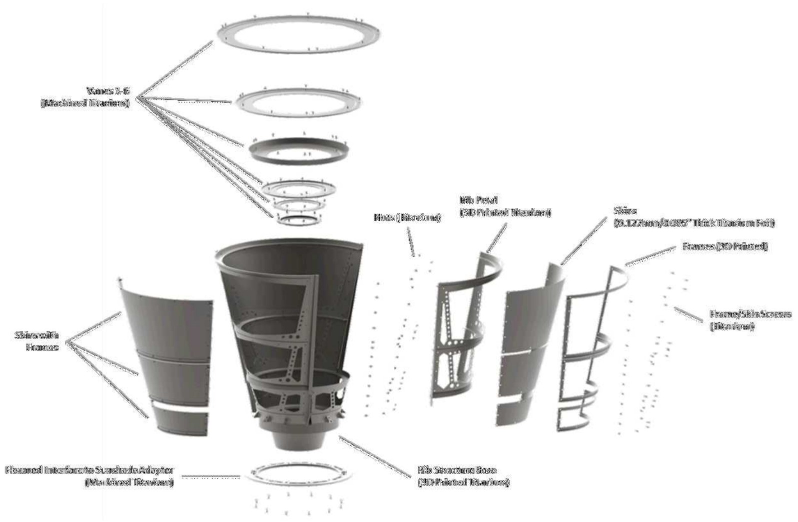


18.2 mm
(0.72")

Additively Manufactured Components (continued)

AM Structure for Lightweight Sunshade

- Baseline design for satellite payload
- AM titanium rib structure with traditionally machined vanes and skins



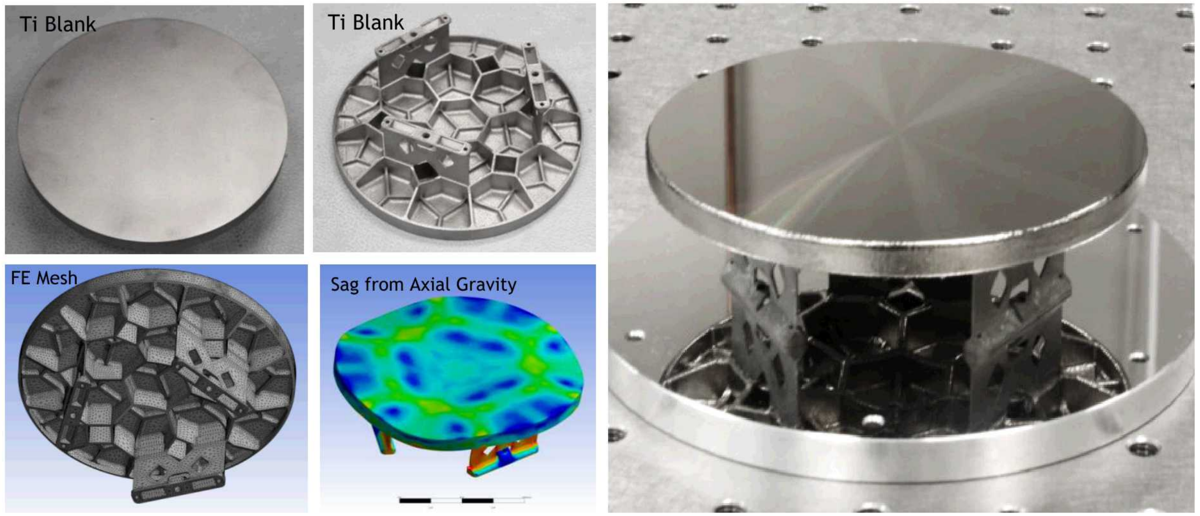

AM Rib Structure Components


Full Assembly

Additively Manufactured Component Studies

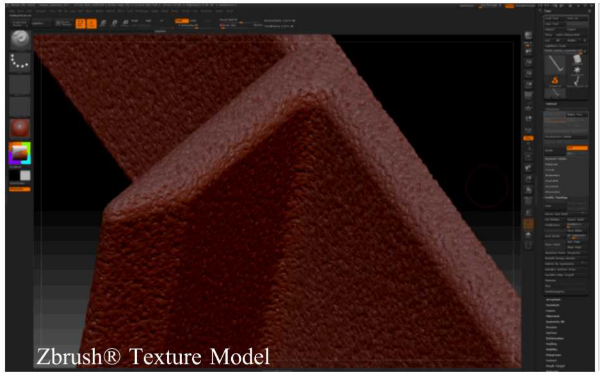
Additively Manufactured Mirror

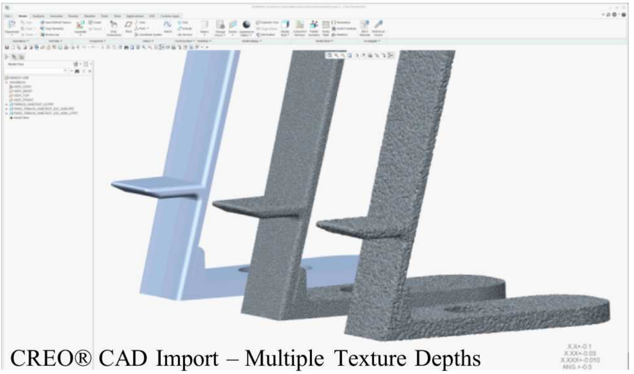
- Lightweight mirror design with integrated flexure mounts
- Nickel plated titanium blank
- Diamond turned optical surface

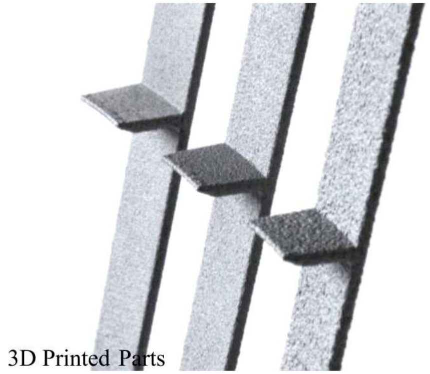


Direct Modeling of Textures

- Textures applied to CAD models in Zbrush®
- For surface reflectivity modification or other uses
- Successfully implemented in additively manufactured components


Zbrush® Texture Model

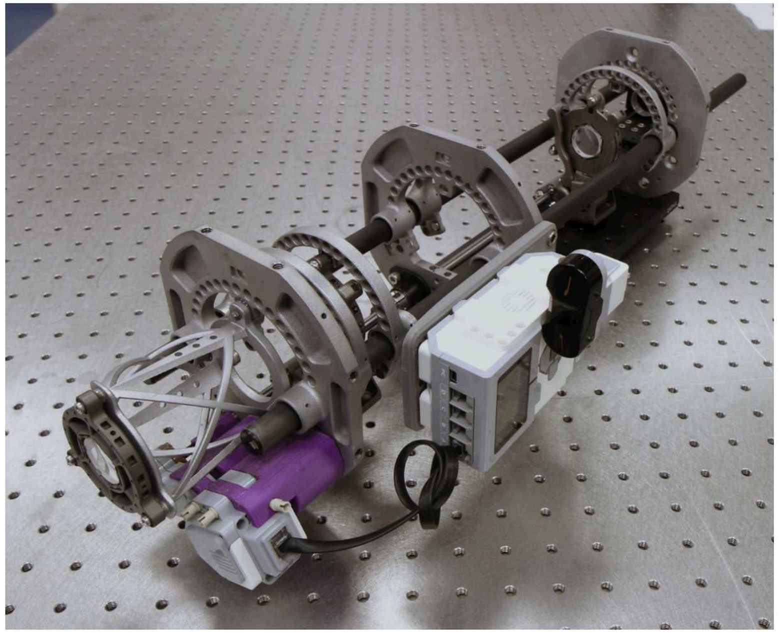

CREO® CAD Import – Multiple Texture Depths


3D Printed Parts

Rapid Production of Precision Systems

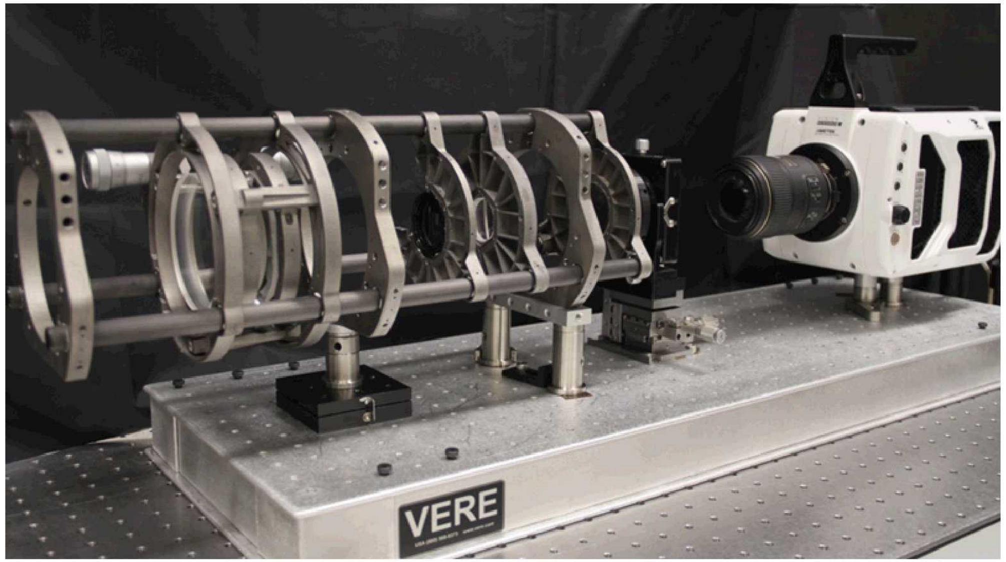
Xoom Concept Testbed

- Early proof of concept for 3D printing, assembly and motion systems
- 2x zooming prototype system with COTS lenses
- Aluminum frames bonded to carbon fiber rails with titanium subcells



Titanium and Carbon Fiber Cage Design

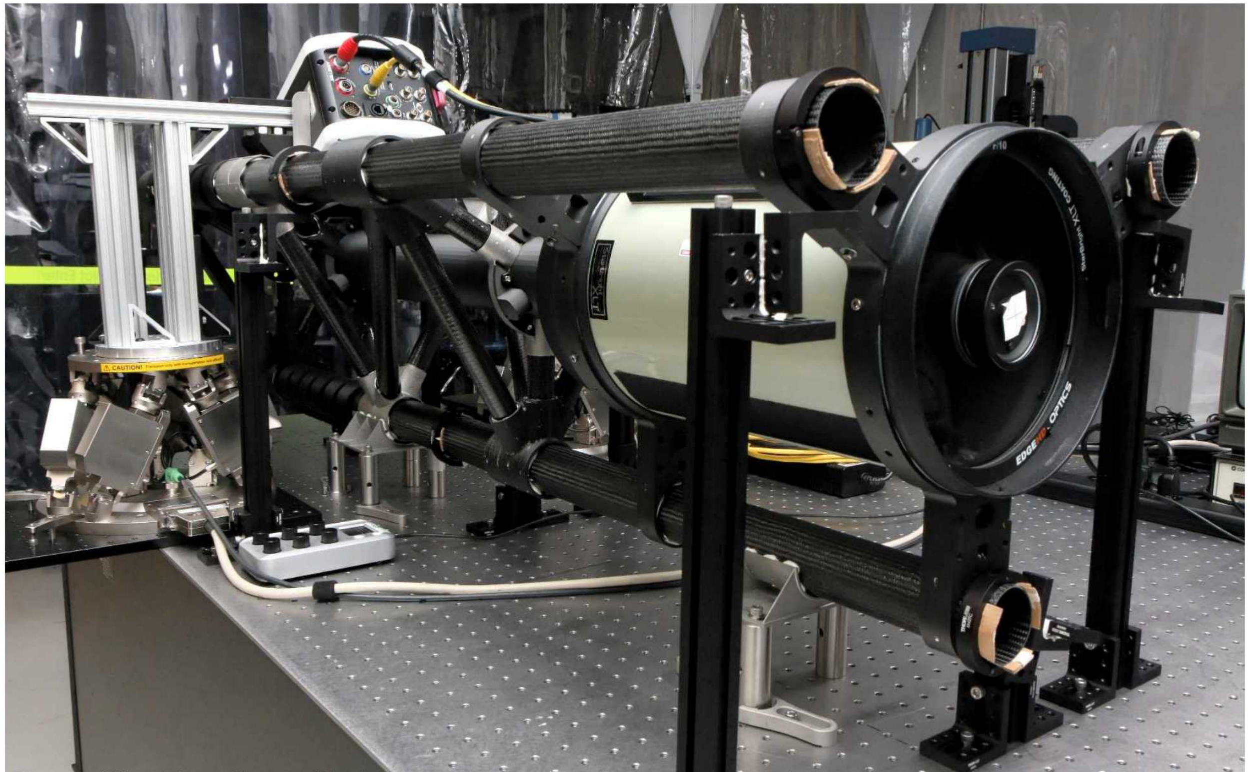
- Modular, lightweight, athermal system design concept
- Titanium subcells bonded to carbon fiber rails
- AM, flexured focus mechanism
- Rapid design/production with actively aligned optics



Rapid Production of Precision Systems (continued)

Large-Scale Carbon Fiber Truss System

- Integrated COTS front-end telescope
- Actively aligned lenses, subcells, and sensors
- Carbon fiber truss structure held with combination of metal and structurally reinforced nylon connector components
- Desktop printer: Markforged, Mark Two
  - Chopped carbon fiber impregnated nylon base material
  - Continuous fiber reinforcement: carbon fiber, Kevlar®, fiberglass
  - Significantly stiffer/stronger than traditional desktop-printed plastic parts (ABS, PLA, photopolymers)
- Design and production methodology well suited for low-cost, rapid realization experimental systems requiring lightweight, athermal, precision structures



Carbon Fiber Truss System During Assembly

Kevlar® (yellow) Reinforced Component During Printing

Conclusions

Additive manufacturing provides an enabling capability for rapid-production, precision, opto-mechanical structures

- Understand and design with AM strengths and weaknesses in mind
- Understand limitations of component and material quality control/verification

Printing capabilities continue to progress

- Scale and precision increases
- Quality control during build
- Continuous fiber reinforced parts
- Ceramic printing of optics
- Embedded electronics, mechanisms, etc
- Rapid "layerless" printing
- Tuneable material properties throughout build

Software continues to catch up to printing capabilities

- Topological optimization
- Optimized lattice structures
- 3D print process analyses modify CAD geometry to compensate for build distortions
- Workflow enhancements, embedded capabilities, solution speeds

Topological Optimization Study for a Mirror Support

Lattice Structure Example*

* Image: "Inspire 2018 Software Release Accelerates Pace of Product Innovation", https://www.altair.com/newsdetail.aspx?news_id=11453&news_country=en-US, 2/1/2018

Thank you for your time.

Rear Relay

Lens Motion

- Drive on smooth shaft with friction nuts
  - Multiple pitch travel on single drive shaft
  - Allows slippage if driven past stopping point
- Lens subcell held by flexible rubber arms to friction nut carrier frame
- Subcells mount kinematically at each end of travel (wide angle and zoom positions) to fixed frames
  - Kinematic mounts use horizontally magnetized pins.
  - Rubber arms on carrier allow small motions to align to kinematic mount
- Fixed frames actively aligned and bonded with lens subcells attached

Motor Mechanisms

- Lego Mindstorms geared stepper motors
  - Lens Drive and Focus drive
  - Battery operated, multi-motor customizable system
  - Easily programmable
  - Remote control
  - Compact and inexpensive

Relay Assembly Attachment

- Entire assembly actively aligned to R-C front section and bonded to triangular frame