Robotic Assembly Concept for the Next Generation Space Telescope

Final Report

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ACRONYMS

CB	Central Baffle
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
IR	Infrared
Isp	Specific Impluse
ISS	International Space Station
JEM	Japanese Experiment Module
L2	Second Lagrange point
MSS	Mobile Servicing System
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NGST	Next Generation Space Telescope
OB	Optical Bench
PM	Primary Mirror
PMS	Primary Mirror Segment
SM	Secondary Mirror
TV	Television

Final Report of a Robotic Assembly Concept for the Next Generation Space Telescope (NGST)

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Introduction

The NGST Project is charged with developing new technologies that will achieve their science objectives while costing much less than the Hubble Space Telescope (HST). As part of this development effort, this study was undertaken to evaluate the possible advantages and disadvantages of a robotic assembly of the NGST telescope. Although robotic assembly technology is not new, its use to assemble a precision optical system in orbit would be new for the National Aeronautics and Space Administration (NASA). The results of the study are that robotic assembly has nine advantages over a conventional automatic deployment. Three are considered major and they are summarized below:

- The diameter of a robotically assembled NGST Telescope will be constrained primarily by cost and weight, not by launch vehicle shroud volume -- The study shows how a robotically assembled 10-meter diameter telescope could easily fit in an Atlas IIARS shroud. This compares to the 8-meter conventionally deployed telescopes that the other NGST studies were able to fit in this shroud. It is expected that mirror technology developments now underway will greatly reduce the cost and weight of the telescope. Robotic assembly assures that if an affordable, lightweight telescope larger than 8-meters in diameter could be built, it will not be constrained to 8-meters by shroud volume. Figures 1 and 2 compare the two packaging approaches.[1]
- A much higher probability of successful deployment **–** It is shown that a single robot will assemble the telescope with a probability of success about equal to the typical automatic deployment. If one flies a second backup robot, the probability of successful assembly becomes a virtual certainty.
- Packaging prevents contamination **–** The launch packaging of the telescope's mirrors for robotic assembly prevents contamination. All mirror surfaces face inward and the spaces between mirrors are closed by a labyrinth seal. A clean gas purge flows through the labyrinth from the inside to the outside. None of the conventionally deployed designs provided similar protection from contamination.

There are two disadvantages to robotic deployment and one is considered significant. It is:

- The cost of the robot **–** This cost is partially offset by the avoided costs of designing, building, and testing the mechanisms that would be needed to automatically deploy the NGST telescope. Another possible cost saving would be the ability to fit the telescope into a smaller launch vehicle's shroud. Suppose the cost and weight constraints allowed building a larger telescope, but conventional deployment would force the use of a larger launch vehicle. A robotically assembled NGST would allow it to still fit in the smaller shroud and the lower cost of this smaller launch vehicle might completely offset the cost of the robots.

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[1] In all illustrations, the various structural parts of the telescope are given different colors to differentiate one part from another. The actual structure will be given a thermal coating that will probably be black.

This report is organized as follows: It first presents a background description of the NGST mission followed by a description of the robot that was assumed for this study. This is followed by a description of the NGST optical components as configured for robotic assembly. This is followed by a step-by-step description of the robotic assembly sequence. Then the nine advantages and two disadvantages of a robotically assembled NGST are discussed. The report ends with an overall summary of robotic assembly of the NGST.

Background

The NGST Mission is envisioned to be NASA's astronomy mission to extend the work of the highly successful HST. The mission is now in an early study phase and a year 2007 launch is planned. A NGST Project Office[2] is located at the Goddard Space Flight Center (GSFC) and is responsible for the overall management of the NGST study. The study draws on engineering and science support from GSFC, other NASA centers, the Jet Propulsion Laboratory, universities, and contractors. The European and Canadian Space Agencies plan to support the project.

The NGST Project has developed a baseline concept for the mission. It is a nominal 8-meter diameter telescope launched by an Atlas IIARS to an orbit around the Sun-Earth second Lagrange (L2) point. Three contractors, TRW, Ball Aerospace, and Lockheed Martin, have also developed NGST concepts. The planned science for the NGST requires that the telescope and instruments be optimized for infrared (IR) measurements. To achieve the required sensitivity, the telescope will be passively cooled to 50K or less. A solar thermal shield will shadow the telescope from the Sun, Earth, and Moon and a thermal isolation mast will position the telescope well above the solar thermal shield and other warm components of the spacecraft. To fit within the Atlas' 3.65-meter inside diameter shroud, the baseline NGST is folded up for launch and then deployed to its operational configuration. The 8-meter diameter Primary Mirror (PM) is made up of 8 segments hinged around an octagonal central mirror. For comparison, the central mirror alone is larger than the HST's 2.4-meter diameter PM.

Description of the Robot used for this Study

The study assumes the robot would be a conventional 7-joint robot with a nominal 6-meter reach. It will be thermally insulated and provided with internal heaters so it can operate properly in any location on the NGST from the warm Sun side of the thermal Sun shield to the 50K anti-Sun side. Each end of the robot will be fitted with an end effector that may be used as a "foot" or a "hand." This allows the robot to "walk" from one Foothold grapple to another. The robot's joint accuracy will be such that the end effector will never be more than 3 cm away from the desired position allowing the robot to maneuver without a collision. When it is to mate with a grapple fitting, the robot uses a television (TV) camera that is aligned with the end effector to view a nearby alignment target. This information will be used to close a control loop allowing the end effector to engage the grapple with very little position error and with near zero force. Since the telescope assembly would be done in the total shadow of the thermal Sun shield, each TV camera incorporates an illumination source. When an end effector is not attached to a grapple, its camera may be used for general viewing. Each end effector also includes a torquer

[2] See the NGST Website, http//ngst.gsfc.nasa.gov/ for scientific, engineering, and programmatic reference materials about the NGST Project.

suitable for loosening or tightening bolts. Its torque axis is aligned with the end effector's axis. Each robot has electronic redundancy (i.e., dual power and data buses, dual motor windings, control circuits, thermal control heaters, and TV cameras) but no mechanical redundancies. It is assumed that the robot's operational control is part of the main NGST computer's program. A separate computer for robot control could be provided, but that would only cost more and lower the overall mission reliability since then both computers would have to work for the mission to succeed.

Operational Control and Safety

For this study, it is assumed that the robot will assemble the NGST telescope under the supervision of a controller on the ground. The controller will send a command to the robot that allows it to do the next step in a preprogrammed sequence. The robot will perform that step and then wait for authority to do the next step. The controller then confirms that the robot did the expected step correctly before allowing it to do the next step.

The controller can also send commands to make adjustments to the robot's position and can command the robot to stop at any time. However, the ~11-second round trip communications time between L2 and the ground controller may make it impossible to stop the robot soon enough if it starts to depart from its preplanned motion. This situation is dealt with by an independent check of the robot's motion done in real time on the NGST. If an abnormal situation were detected, it would stop the robot by turning off the power to the joint motors and engage the joint brakes. The ground controller would then have time to correct the problem.

Robot Grapple Attachments

The robot uses a grapple fixture that may be used in three functionally different ways. The three functions are:

1. **Foothold –** The Foothold grapple accurately fixes one end of the robot in all 6 degrees of freedom. It is mounted to a structure that is able to react the highest forces and torques that the robot arm can generate. It includes primary and redundant connections for power and primary and redundant digital data buses for sending and receiving robot telemetry, command, and TV data. A captive bolt within a Foothold grapple may be loosened or tightened by the robot's end effector. These bolt torques are reacted by the Foothold grapple.
2. **Handhold –** The Handhold grapple is provided on those parts that the robot is to assemble. Like the Foothold grapple, it provides an accurate positioning and orientation of the robot to the part, but it may be mounted on lighter weight structure since the forces and torques it must react are small. An electrical connection can be provided if power and/or control signals are required by the part while it is being carried by the robot. A captive bolt is located within all Handhold grapples. The torque to loosen or tighten the bolt is reacted by the Handhold grapple and not back through the robot to the Foothold grapple.
3. **Grapple –**A grapple is provided to position the end effector over a bolt so the robot's torquer can loosen or tighten it. These fittings are not used as Handholds or Footholds and have no electrical connectors. When loosened, the bolt is retained by the grapple

and cannot become free. The torque to loosen or tighten the bolt is reacted by the grapple and not back through the robot to the Foothold grapple.

The design of the grapple fitting will be up to the robot contractor. The fixture shown in the illustrations is a design by Spar Aerospace Ltd.

The assembly sequence for a typical NGST part is as follows: one end of the robot stands on a Foothold and the other end releases the bolts that hold the part in its launch position. When the robot releases the last bolt holding the part in place, the robot will be connected to the part by a Handhold grapple. The robot then moves the part to its destination, accurately positions it, and tightens the bolt under the Handhold. The mechanical interface under this bolt includes V-guides to accurately align the part. The robot then tightens other bolts on the part to finish the assembly.

All parts assembled by the robot have at least two Handholds and/or Footholds. The second Handhold or Foothold is used by the backup robot should the primary robot fail while carrying a part. This transfer operation is discussed in a later section of this report.

Description of the Elements of the NGST Telescope

There are five major components of the NGST telescope that are assembled by the robot. They are:

1. **The Optical Bench (OB) –** At launch and after assembly, the OB supports all the parts of the NGST optical system as well as the scientific instruments. It is a circular structural plate a little smaller than the diameter of the Atlas shroud. It is launched in the cylindrical section of the shroud, just below the conical section and perpendicular to the long axis of the Atlas vehicle. Three Footholds are provided, spaced 120-degrees apart around the edge of the OB.

2. **The Primary Mirror –** The PM is composed of twelve slice-of-pie-shaped PM Segments (PMS) that will be assembled by the robot onto the OB to form the telescope's 10-meter diameter PM. The segments are numbered PMS-1 through PMS-12. Figures 3a and 3b show a PMS mirror side and structure side.

   The PMSs are packaged for launch in three sets of four nested PMSs called a 4-pack. Figure 4 shows two views of a 4-pack. The 4-pack 1 is made up of PMS-1, -2, -3, and -4. The PMS-1 is bolted to PMS-2 in three places. The mirror side of PMS-1 is innermost and its structural side faces outwards. The mirror side of PMS-2 faces the structure side of PMS-1 and its structural side faces outwards. In the same way, PMS-3 mounts to PMS-2, as does PMS-4 to PMS-3. The same arrangement of mirror segments makes up the second 4-pack, PMS-5 through PMS-8, and also the third 4-pack, PMS-9 through PMS-12. For launch, the three 4-packs mount to the OB at 120-degree intervals by two bolts at their wide ends. Their narrow ends are above the OB and fit inside the narrow conical part of the launch vehicle's shroud. At the narrow end of each 4-pack, an integral bracket is bolted to its neighboring 4-pack.

   A labyrinth seal would be provided between the OB and the edges of the 4-packs. Similarly, a labyrinth seal is provided between the long sides of the 4-packs. For the sake of clarity, the labyrinth seal is not shown in any of the illustraions.

3. **The Secondary Mirror (SM) Assembly –** The SM is an 830-mm diameter mirror that will be assembled by the robot on a tripod structure and positioned 11.5 meters above

the PM. The SM assembly consists of three parts: the SM, a SM support structure, and a Stewart platform that holds the SM to the SM support structure. The Stewart platform can adjust the SM in 6 degrees of freedom. The SM support structure includes a SM baffle 1.17 meters in diameter.

During launch, the SM, the SM Stewart platform, and SM support structure are fully assembled to each other and bolted to the narrow ends of the three 4-packs by three bolts. A close-up view of this mounting is shown in Figure 5. The SM mirror faces inward. The SM baffle extends down around the SM mirror and includes a labyrinth seal that seals the space between the SM and the top ends of the three 4-packs. For clarity, this baffle and seal are not shown in Figure 5.

4. **The SM Tripod –** The SM Tripod consists of three legs; each almost 12 meters long when fully assembled. During launch, a folded Tripod Leg is stowed on the outside (back) of each 4-pack.

   The three Tripod Legs are identical and consist of six lengths of a tapered tubular structure with hinges connecting one length to the next in series. Each hinge joint includes a detent mechanism to temporarily hold the joint's position in 5-degree increments as the robot opens it. When a tripod joint is opened to its fully deployed position, the robot engages a grapple at that joint and tightens a bolt. A pair of radial V-guides precisely aligns the joint in all axes. Note that the hinge is not part of this alignment. All hinges will have a small amount of free play to eliminate the need for lubrication while ensuring no binding of the hinge during assembly at any temperature.

   In addition to the joint grapples, each Tripod Leg has two Handholds and three Footholds. The two Handholds are mounted at the end of the leg segment that attaches to the OB. One Foothold is mounted near the other end of the same segment ~3 meters above the OB end. A second Foothold is mounted on the fourth segment ~9 meters above the OB when the Tripod Leg is fully extended. A third Foothold is provided at the end of the last segment. It attaches to the top of the SM structure.

   A continuous electrical cable runs inside each Tripod Leg from one end to the other. When the robot attaches a Tripod Leg to the OB, this cable is electrically connected to the NGST and the three Footholds on the Tripod Leg become electrically active. Similarly, when the robot attaches the first Tripod Leg to the top of the SM structure, all SM electronics become electrically active. When the other two Tripod Legs are connected to the SM structure, they provide redundant electrical paths to the SM-mounted electronics.

5. **The Central Baffle (CB) –** The CB consists of two nested cylindrical tubes concentric with a central hole in the OB. The inner baffle tube is fixed to the top surface of the OB. During launch, the other baffle tube is stowed just above the OB and attached to the inner baffle tube by six bolts. Three of the bolts are located at 120-degree intervals around the top end of the outer tube and three are similarly spaced around the tube at its bottom end. A grapple is provided for each of the three top-end bolts and a Handhold is provided for each of the three bottom-end bolts.

The Robotic Assembly Sequence

Deploy the Robots

The robots would be stowed for launch with other warm spacecraft components on the warm side of the Sun shield until the assembly of the telescope is to begin. At that time, the robots will walk around the edge of the Sun shield, traverse the isolation truss, and attach themselves to Footholds on the edge of the OB. The placement of Footholds needed for walking from the storage location to the OB were not part of this study. Also, the details of the robots' storage attachments will be the responsibility of the robot manufacturer and are not part of this study.

The First Robot Task –Assemble the SM Tripod Legs and the SM

Figure 6 shows this assembly sequence. The primary robot would stand on the OB Foothold that is nearest 4-pack 1 and unscrews all bolts that keep the sections of Tripod Leg 1 folded during launch. It then unscrews the bolts holding the folded Tripod Leg 1 in its stowed location on the outside (back) of PMS-4. The last mounting bolt to be unscrewed will be under the Handhold that the robot uses to move the leg into position and the same bolt then attaches the leg to the OB. The robot releases that Handhold, grasps the adjacent Handhold, and tightens the bolt under it. Precise alignment of the Tripod Leg is provided by a crossed V-guide that is built into the interface between the Tripod Leg and the OB.

The robot then walks to the Foothold on the upper end of the first section of the Tripod Leg and releases the Foothold on the OB. Then it grapples the second Foothold on the fourth section of the Tripod Leg and moves it so that hinges 1 and 2 open to ~30 degrees each. It then rotates the fourth section by 180 degrees so that sections 3 and 4 are in line. Detents in each hinge retain these angles. It then attaches to the grapple on hinge 3 and tightens the bolt firmly locking that joint. The crossed V-guide built into this joint aligns it and the bolt prevents any further motion. The robot then grapples the third Foothold on the far end of the Tripod Leg. It moves that Foothold to a position at the top of the SM structure, aligns it, and tightens the bolt. Then it releases the third Foothold and attaches to a grapple on the SM structure and unscrews one of the three bolts that attach the SM structure to a 4-pack.

The robot then walks to an adjacent OB Foothold and repeats this same sequence to attach Tripod Leg 2 between the OB and the SM structure. Similarly, when it has finished attaching Tripod Leg 2, it walks to the next OB Foothold and again repeats the same sequence for Tripod Leg 3. At this point, the SM structure is attached to the OB by the three Tripod Legs and is no longer bolted to the top of the 4-packs.

While still standing on the Foothold at the upper end of the first section of Tripod Leg 3, the robot attaches to one of the Footholds on the top of the SM structure. It then raises the SM structure to straighten out hinge joint 4 of all three Tripod Legs and then tightens the bolt that locks joint 4 on each leg. The robot then grapples the second Foothold on section 4 of Tripod Leg 3 and extends itself so that all tripod sections are in their final straight position. It then tightens the joint bolts 1, 2, and 5 on each leg. The positioning of the SM is now complete.

Second Robot Assembly Task – Temporary Repositioning of the 4-packs and Assembly of the CB

Figure 7 shows this assembly sequence. The CB is stowed in the central volume inside the three 4-packs and above the OB. To reach the CB, the robot first repositions each 4-pack to a temporary location on a Tripod Leg. To do this, the robot stands on the OB Foothold at the outer edge of the first 4-pack and unscrews the inboard bolt that holds the 4-pack to the OB. It then unscrews the top-end bolt that attaches the adjacent 4-pack to the first 4-pack. It then attaches to the Handhold at the top end of the first 4-pack and unscrews the bolt that attaches it to the other adjacent 4-pack. While still attached to this Handhold, it releases the last bolt under the Foothold. The robot then positions the 4-pack at a temporary location on the adjacent Tripod Leg and attaches it there. This attachment point is aligned with the lowest Foothold on the tripod and on the side opposite the Foothold. The robot then unbolts the six lower bolts that hold the PMSs to each other. Each PMS is now held to the next PMS by one bolt at its narrow end. It repeats this procedure for the other two 4-packs.

The robot then loosens the three bolts around the top of the outer section of the CB and the three bolts around the bottom of the same section. Using the last lower Handhold, the robot raises the outer section of the CB into its operating position and tightens the bolt under the Handhold. Figure 8 shows this assembly sequence. Internal mechanical stops between the two sections of the CB align the upper section at its proper height and rotation. The robot then tightens the other two lower bolts. The CB is now fully assembled. Note that the final locations of the grapples over the six bolts will not contribute any blockage of the PM because they are in the shadow of the Tripod Legs.

Third Robot Task – Assembly of the PM

As shown in Figure 8, the PM assembly sequence starts with the PMSs packaged in three 4-packs and each 4-pack is attached by one bolt to a Tripod Leg. The robot then walks to the first Foothold on Tripod Leg 1 and attaches to the Handhold grapple at the narrow end of PMS-1 and unbolts the bolt under this Handhold freeing PMS-1. The robot then carries it to its operating location and attaches it. Depending on the mirror technology, the PMS may be mounted directly to the OB or it may be mounted to a Stewart platform. In either case, this attachment point includes a pair of radial V-guides that precisely align the PMS-1 in its final position. If Stewart platforms are used, each of the 12 Stewart platforms would be launched already attached to the OB with a mounting plate that mates with the back of a PMS.

Figure 9 shows the robot repeating this sequence of operations with PMS-2 and PMS-3. In each case, the robot approaches the final location of the PMS in radial direction in a plane parallel to and well above the adjacent PMS that has already been mounted. Because the rear edges of the PMS are beveled, the part being moved cannot contact a PMS that is already mounted even if the robot's position is at its maximum error. When the PMS is located above its final location, the robot's TV camera will be able to see the target on the OB and correct any errors in its position before it starts to lower a PMS onto its mounting structure.

This leaves PMS-4 attached to the Tripod Leg with one bolt. The robot attaches itself to the Handhold grapple at the top of PMS-4. While holding this Handhold, the Foothold torquer unscrews the bolt that attaches the PMS to the Tripod Leg. The Foothold torquer unscrews it using the bolt end that is opposite the bolt head normally used by the robot. It then assembles PMS-4 to its location on the OB or Stewart platform.

The robot then walks to an adjacent OB Foothold and tightens the remaining bolts that attach the backs of PMSs 1 through 4 to the OB or Stewart platforms.

The robot then moves to the same location on Tripod Leg 2 and repeats the above procedure for PMS-5, -6, -7, and -8.

The robot then moves to the same location on Tripod Leg 3 and repeats the above procedure for PMS-9, -10, -11, and -12 except that it can no longer directly reach a Foothold on the OB, but must walk around the edge of the now complete PM. To do this, the robot attaches to a Foothold provided on the outer edge of either PMS-4 or PMS-8. Figure 10 depicts this maneuver. From this Foothold it can walk to Footholds on the OB and complete bolting the backs of PMSs -9 through -12.

After finishing the assembly of the telescope, each robot reverses its original deployment sequence and stows itself on the warm side of the solar thermal shield.

<u>Transfer of Assembly Tasks to the Backup Robot</u>

The backup robot would normally follow the primary robot from its storage location and then position itself so that its TV camera could provide confirmation images of the primary robot's progress. Should the primary robot experience a failure during the telescope assembly, the backup robot will take over and complete the assembly of the telescope. Examples of various primary robot failures are presented below with the procedure that the backup robot would use to take over and complete the assembly.

A Redundant Component Fails

Normally, the primary robot would operate using the A side of each redundant component. Should there be a failure in the A side, a ground command would switch to the B side for that component. The robot could then continue its operation until a convenient stopping point was reached. The backup robot would then continue with the assembly and the primary robot would position itself to provide confirmation images.

A Joint on the Primary Robot Fails

Since there are seven joints and only 6 degrees of freedom are required, the primary robot will retain some range of motion. In the worst case, it would be carrying a part and the failure would prevent it from stowing the part. In this case, the backup robot would attach to another Handhold on the part and the primary robot would release the part. The backup robot would then temporarily stow the part. The failed robot would move to another Foothold if it were able. If not, the backup robot would attach to a Handhold on the failed robot, the failed robot would release its foothold and the backup would reposition the failed robot's end effector over another Foothold and it would grapple it. Once the failed robot was safely out of the way, the backup robot would finish the assembly. The failed robot would probably still be able to provide confirmation images to the ground.

The Primary Robot's End Effector Fails to Release a Grapple

If the mechanism that attaches to a grapple fitting fails to open, the primary robot would not be able to release the part that it was attached to. This failure would not be obvious until the robot was to release a grapple. The backup robot would engage a grapple on the side of the failed end effector and using its torquer, activate an emergency release mechanism. The backup robot would then attach to a Handhold on the failed robot, the failed robot would release its Foothold, the backup would reposition the failed robot over another Foothold and it would grapple it. The backup robot would then continue the assembly.

The Primary Robot's End Effector Torquer Fails

If one of the primary robot's torquers failed, it could still move around on its own, but it could no longer tighten or loosen bolts with the end effector. It would simply park itself out of the way and the backup robot would take over. If it were carrying a part when this failure occurred, the backup robot would grapple one of the other Handholds and the failed robot could release the part and walk to another location out of the way. The backup robot would then temporarily stow the part so it could change Handholds and then continue the assembly.

If the primary robot's failure prevented it from walking back to its storage location, the backup robot would grapple the failed robot and position the end that still works over a Foothold and activate the end effector. It would release the failed robot, walk to the next Foothold, reach back for the failed robot, grapple it, and reposition it over the next Foothold. This requires that additional Footholds be placed along any path to be taken by the robots.

<u>Discussion of Advantages</u>

There are nine advantages for using a robot to assemble the NGST telescope rather than a conventional automatic deployment. These are listed below:

1. *The Diameter of a Robotically Assembled NGST Telescope will be Constrained Primarily by Cost and Weight, not by Launch Vehicle Shroud Volume*

Conventional deployment requires that the parts to be deployed be located close to their deployed location during launch in order to keep the deployment mechanisms simple and reliable. Robotic assembly allows launch location of each part to be located anywhere within the launch shroud. The 10-meter diameter PM design of this study would be launched as 12 identical mirror segments nested together with their narrow ends up to fit within the conical section of the shroud. Figure 1 shows these two NGST design concepts ready for launch.

Not only is the telescope larger, the remaining usable volume of ~44m^3 in the shroud is ~12m^3 larger than the ~32m^3 available for the baseline 8-meter diameter telescope concept. This additional volume provides an option not possible to the baseline concept, namely, the volume to add a high specific impulse (Isp) third stage to the NGST. The addition of a high Isp stage would allow the same basic vehicle to launch the extra mass of a larger telescope. Alternatively, suppose the lightweight mirror developments do not fully meet their goals. The high Isp stage would then allow a heavier 8-meter diameter mirror to be launched without having to buy a larger launch vehicle.

Another way to look at the high packaging efficiency is to realize that if the 10-meter roboticly assembled design were scaled down to be optically equivalent to the baseline 8-meter design, it could fit into the much smaller 2.74-meter shroud of a Delta II. The difference in cost between an Atlas IIARS and a Delta II would pay for the robot.

Similarly, the same 12-segment primary design could be scaled-up and launched in a Delta IV's 5-meter diameter shroud to provide a 13.5-meter diameter NGST telescope. A similar scale-up of the reference design would allow only a 10.5-meter NGST telescope diameter.

Even larger primaries are possible with robotic assembly. For instance, if one increased the number of primary segments from 12 to 15, a 16.8-meter primary could fit in a Delta IV shroud. Increasing the number of mirror segments to 18 would produce a 20-m diameter telescope. A mirror of these larger sizes is probably beyond today's mirror making state of the art, but when such large mirrors actually can be built, they can be launched provided a robot is used to assemble them. Table 1 summarizes these options.

Table 1 -- Possible Telescope Diameter (meters)

	Delta II 2.743-m Shroud	Atlas IIARS or Delta III 4-m Shroud	Delta IV 5-m Shroud
Automatic Deployment	6	8 NGST Baseline	10.5
12-Segment Robotic Assembly	8	10 This study's design	13.5
15-Segment Robotic Assembly	-	12.5	16.8
18-Segment Robotic Assembly	-	-	20

The packaging efficiency of a robotically assembled telescope assures that the telescope size will not be limited by packaging considerations. Only its mass and/or the dollars available to build it will limit its size.

2. Higher Probability for a Successful Robotic Assembly[3]

It is estimated that a robot has a chance to successfully assemble the telescope of better than 40:1. Because robotic assembly is a new technology used in a critical application, this study assumed that two robots would be flown and that either robot could do the job. The second robot virtually guarantees a successful assembly since together they have a probability of a successful mirror assembly of 1600:1. While one robot should be able to assemble the NGST telescope in a few days, to be conservative, the reliability calculation assumed that each robot operated in orbit for 32 days over a 6-month period.

The robots would be built using space qualified parts such as motors, angle encoders, and bearings that have successfully flown on NASA missions to point antennas and solar arrays. These flight actuators are typically directly driven with no gears or brakes. For the

[3] Reliability Estimate based on actuator reliability estimates for the Flight Telerobotic Servicer Program by Moog, Inc., Schaffer Magnetics Division, Report 114177.

robot, a single harmonic gear reduction and a brake would be added to each joint motor to achieve the needed running, stopping, and holding torques with low motor power consumption. The end effector torquers that tighten and loosen bolts would be similar to the joint actuators, but would not include a brake.

An estimate of the success of a conventional deployment of a NGST must wait until the design of the actual telescope parts and their deployment mechanisms become available. However, estimates can be made of the reliability needed for each deployment mechanism so that the total reliability matches a single robot's 40:1 probability of success or the dual robot's 1600:1 probability of success. In the baseline design, there are 8 mirror segments that use a hinge-type mechanism and the SM is deployed by a linear motion mechanism. If all 9 mechanisms have equal failure rates, they would each need to have a probability of successful deployment of 356:1 to match the single robot probability of successful assembly and 14,396:1 to match the dual robot.

Although the vast majority of conventional deployment mechanisms that have flown have had successful operation in space, there have been recent failures. The communications satellite EchoStar 4 has been declared a total loss because its solar panels did not deploy properly. Also, one of the two solar panels on the Mars Global Surveyor did not deploy all the way and lock. In contrast, there have been no recent reports of failed actuators that drive antenna gimbals or solar array drives.

3. Packaging Prevents Mirror Contamination[4]

Robotic assembly allows the packaging of all optical surfaces so that they cannot be contaminated during ground handling, launch, and during the deployment of the non-optical parts of the NGST. The packaging places all mirror surfaces so that they face inward and then sealing the gaps between the backs of the outermost mirrors with labyrinth seals. Then a continuous flow of clean gas is made to flow from the inside to the outside through the zigzag path of the labyrinths keeping any contamination from reaching the mirror surfaces. Once the mirror contractor assembles the mirrors to the OB and the clean gas starts to flow, the mirror assembly can move through the various integration and test operations with assurance that mirror contamination will not occur. During launch, the rapid depressurization of the shroud as the rocket ascends above the atmosphere simply increases the flow of gas out through the labyrinth and any particles that are shed by the shroud's acoustic blanket are kept out. After the major propulsion events are executed and the NGST is on its trajectory to its orbit about L2, the non-telescope NGST deployments

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[4] If the PM or SM becomes contaminated, the NGST will produce poorer signal-to-noise images than it would if no contamination occurred. There are two kinds of contamination: molecular and particulate. A layer of molecular contamination attenuates the amount of starlight reflected from the mirror. The amount of attenuation depends on the kind of molecule, the thickness of the layer, and the wavelength being observed. The main sources for molecular contamination are the rocket exhaust products and outgassing from the NGST. Particulate contamination is of special concern for the NGST telescope as it does not have an exterior cylindrical baffle to block most of the off-axis light. Without such a baffle, contaminating particles on the mirrors will be illuminated by off-axis light from Stars, Planets, and the solar thermal shield. The particles will absorb some of this light and the rest will be diffusely reflected. The absorbed light will raise the temperature of the particle and it will then be reradiated in the IR. Some of the reradiated light and some of the diffuse reflected light will enter the instruments as if it were light from the on-axis Star field. This light is noise in the image and limits the telescope's ultimate performance.

would be made. The robotic assembly of the telescope would be delayed for a week or so to give any contamination time to either escape to space or to adhere to some non-mirror surface.

The baseline NGST design does not provide any similar contamination protection for the telescope optics. This means that to achieve the equivalent low mirror contamination of the robotic design, extreme care and attention to air cleanliness will be required at every point in the buildup of the NGST. Wherever the mirrors are located during the NGST integration, test, transportation, and mating to the launch vehicle, they must be in a high quality clean room. Every component part of the NGST and every handling procedure will require special attention to cleanliness. The acoustic blankets that line the shroud will require special treatment to prevent shedding of particles.

An alternative for the baseline NGST design is to add contamination protection devices. For instance, a contamination cover could be put over each mirror. These would protect the mirrors throughout the NGST buildup and launch and would be commanded to uncover the mirrors a week or so after the NGST achieves its trajectory to the L2 point. Although the contamination protection mechanisms will add some costs, that cost will probably be less than the added costs that will be spent keeping an unprotected NGST clean on the ground and inside the launch vehicle's shroud.

4. A Larger Optical System Will Return More Science

The baseline 8-meter diameter PM is not a fully filled aperture because it has gaps and triangular cutouts between the 8 segments and a central hole. Its area is ~42 m^2, which is equivalent to a fully-filled mirror of 7.3-meters diameter. The robotically assembled 10-meter diameter PM is almost fully filled with only small gaps between the mirror segments and the central hole. Its mirror area is ~75.5 m^2 equivalent to a full aperture mirror of 9.8 meters. Figure 2 compares the two designs.

For some tasks, the performance of a telescope is proportional to the diameter to the fourth power[5] giving a 10-meter telescope 2.44 times more performance than an 8-meter telescope. This means that during the nominal 5-year mission life of the NGST, a 10-meter diameter NGST telescope will return more than twice the science of the baseline 8-meter NGST.

5. Total Qualification of the Robot and the NGST Assembly Process Before Launch

The robot would be built from space-qualified components and then thoroughly ground tested. If desired, it could be space qualified on a Shuttle flight or on the International Space Station (ISS).

The telescope assembly sequence would be demonstrated in a neutral buoyancy water tank using simulated NGST components. These components would match the size, shape, and the mechanical interfaces of the actual components, but would have a density equal to water. Since the test is done with simulated NGST parts, it can be run in parallel with the integration and test of the actual NGST.

For a conventional deployment of the NGST, some component testing will be possible before launch, however, it is unlikely that a test of the complete conventional deployment

[5] A discussion of telescope performance is given in The Next Generation Space Telescope – Visiting a Time When Galaxies Were Young, p 30, edited by H.S. Stockman, available on the NGST Website.

system can be done in 1 g. What testing is done must use actual NGST components and so will be scheduled in series with all the other NGST work. The test conditions must closely simulate the vacuum and temperature the mechanisms will be operated in.

6. No Mechanical Shocks From Explosive Bolts

All robotic assembly operations are made with simple bolts that are operated by the robot. No mechanical shock is created when the robot loosens a mounting bolt. In contrast, conventional deployments typically use explosive bolts that impart shocks in excess of 1000 g. Any NGST components located near one of these bolts, such as mirror actuators, will have to be built to reliably withstand these shock loads.

Besides the damage that may be directly caused, these mechanical shocks can dislodge loosely adhered particles. Once dislodged, they will be free to contaminate the mirrors. The loosening or tightening of bolts by a robot will not dislodge any particles.

7. The Robot's TV Cameras Give Visual Confirmation of the NGST's Configuration

The robots will have dual TV cameras and light sources at each end. The primary use of these cameras is to view a target that provides fine position control of the robot as it engages a grapple fitting or attaches a part it is carrying. When not viewing these targets, the robot can position and aim its camera and light to look at any part of the NGST. During telescope assembly, the primary and backup robots would provide visual confirmation of the assembly work as it progresses.

This telepresence could also be used to diagnose problems. For instance, suppose the solar array did not fully deploy. The robot could show what had happened and perhaps fix the problem. It could also look for micrometeoroid damage to the mirrors or other parts of the NGST.

All TV images would be available for distribution to the public.

8. A Robot on the NGST Could be Used for Other Assembly Tasks

The present study was limited to just the robotic assembly of the optical system and did not cover any other assembly tasks. However, a robot that can assemble the PM and the SM can assemble anything else. For instance, the robot could assemble (or assist) a conventional deployment of the solar array, the Sun shield, the thruster boom, and the thermal isolation truss.

9. Some Servicing of the NGST During its Lifetime is Possible

A resident robot gives the NGST the ability to replace any failed component for which a spare component was provided at launch. For example, the robot could replace a failed Stewart platform with a spare. To do this, the robot would disassemble the PMS from the failed Stewart platform and temporarily stow it on a nearby Tripod Leg. It would then unbolt the central bolt holding the Stewart platform interface structure to the OB. This grapple is shown in Figure 3a. Then the robot relocates the failed Stewart platform to a storage location to the rear of the OB, picks up a spare, and reassembles the Stewart platform and PMS. It is possible to make the Stewart platform design for the SM and PM identical so that the same spare Stewart platform could back up either location. For another example, if the PM technology required shape control by hundreds (or even thousands) of actuators, the probability of a failed actuator during the life of the mission is high. A robot could easily replace any failed actuator and thereby restore full operability to the NGST.

Discussion of a Disadvantage

There are two disadvantages to using robots to assemble the NGST. They are listed below:

1. The Cost of the Robots

The development and production costs of suitable NGST robots will be significant. Some of this cost would be offset by the avoided cost of designing, building, and testing the conventional mechanisms that would be needed if the robot were not used. Another possible cost advantage of the robot is the possibility of using a smaller, lower-cost launch vehicle because of the more efficient packaging of the telescope that is possible with robotic assembly.

One potential way to lower the cost would be to modify one of the three ISS robot developments for use on the NGST. The ISS robot developments are listed below:

- Spar Aerospace Ltd.[6], under contract to the Canadian Space Agency, is building the Mobile Servicing System (MSS). The MSS can pick up a Special Purpose Dexterous Manipulator. It is a smaller, two-armed robot with tactile capability that will handle many of the servicing and assembly tasks currently performed by astronauts on space walks. The NGST Project has funded Spar to study a robot derived from their ISS robots that could do the robotic assembly of the NGST.
- The National Space Development Agency of Japan (NASDA) is building the Japanese Experiment Module (JEM)[7] Remote Manipulator System. It will change out Orbital Replacement Units mounted on the JEM-Exposed Facility and consists of a main arm that is about 10 meters long and a second, smaller arm that is about 1.5 meters long. The main arm picks up the smaller arm when fine operations are desired.
- Fokker Space B.V.[8], under contract to the European Space Agency, is responsible for the design a robotic arm to be used to assemble the Russian segment of the ISS and to deploy its solar arrays and thermal radiators. It has a reach of 11.3 meters and can "walk" from place to place on the ISS wherever its grapples are provided.

2. The Weight of the Robots

Without an actual design for both a conventional deployment and a robotic assembly of the NGST, the true weight penalty or advantage cannot be determined. To be conservative, this report carries the weight of the robots as a possible disadvantage.

One robot, including the various grapples that it needs to do its job, will probably weigh a little more than the conventional deployment mechanisms that would not be needed. To ensure nearly 100-percent assembly success, a backup robot is included in this design study and this makes the weight penalty larger. But for a given size telescope, the structure of the individual PM segments will be lighter for robotic assembly. This is because the 4-pack nesting of the segments has a naturally higher stiffness compared to the

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[6] See the Spar Aerospace Ltd. Website at: http://www.spar.ca/space/mms.htm
[7] See the NASDA Website at: http://jem.tksc.nasda.go.jp/JEM/Jem-j/mfd/mfddoc1_e.html
[8] See the Fokker Website at: http://www.fokkerspace.nl/products/robotics.htm

individual PM segments. Then, the triangular arrangement of the 4-packs has a high natural stiffness not possible in the square configuration of the baseline design. (In most designs, the structural weight is determined by required stiffness, not strength.) Also the load paths within a PMS are shorter because launch loads are applied to the wide (heavier) end of the segments not the narrow end as in the baseline design.

It is likely that the structural and mechanism weight savings for a robotically assembled telescope will be enough to pay for the weight of the two robots and their grapple fittings.

Summary

Using a robot to assemble the telescope of NGST is technically feasible and has nine advantages over a conventional automatic deployment. The three most significant advantages over a conventionally deployed telescope are:

1. The PM size can be larger for a given launch vehicle shroud. This assures that the largest possible lightweight, low cost telescope can be packaged within a given launch vehicle's shroud. The mirror size will not be constrained by the shroud volume.
2. The probability of successful assembly will be much higher.
3. The packaging makes contamination of the mirrors negligible.

Advantages 1 and 3 greatly improve the science that the NGST will return. The larger the telescope and the cleaner the telescope, the higher the quality of the images and spectra that the NGST will produce. The second advantage insures that the NGST actually becomes operational. With a conventional deployment, if any part does not fully deploy, the mission is over. With a robot, there is always an opportunity to correct some unexpected problem and save the mission.

The major disadvantage to robotic assembly is the cost to develop the robot. This is partially offset by avoiding the development costs of the conventional deployment mechanisms and their testing. Also, the packaging advantage of robotic assembly may make it possible to use a lower cost launch vehicle for a given size telescope.

Once a robot is developed, it would enable the robotic assembly of other Origin missions with large optics and/or large structures. Some of these missions will be very difficult to construct on orbit using conventional automatic deployment technology. With this long-term view, the development of a robot for NGST would be a worthwhile investment.

Fig.1 -- Packaging Efficiency

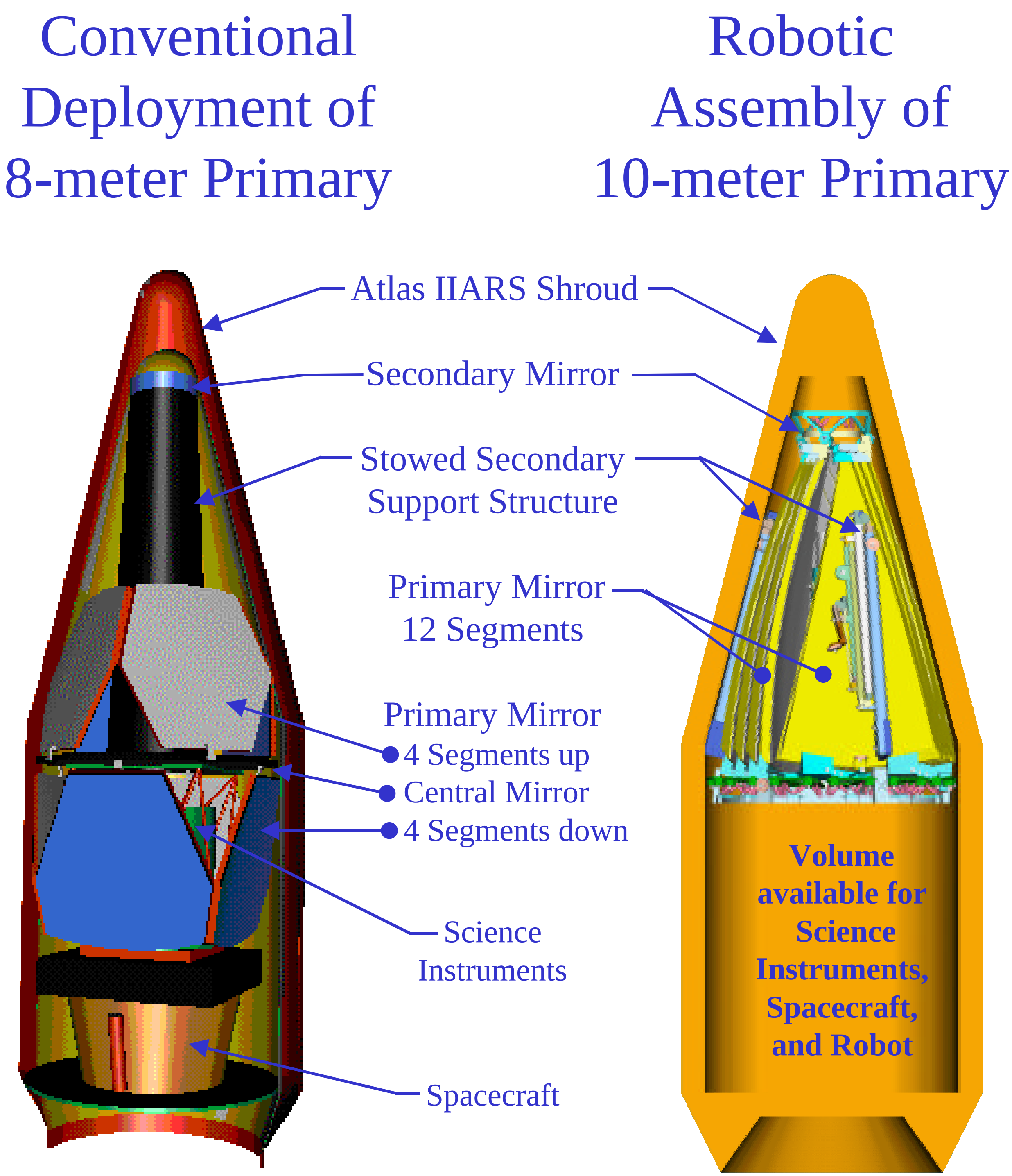
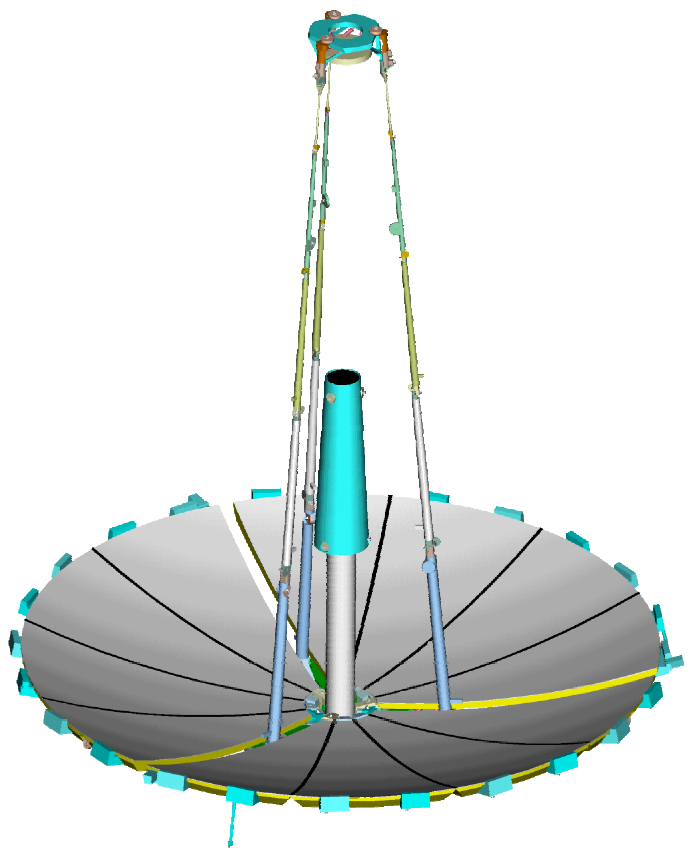


Figure 2 -- Robotic Assembly Allows Larger Telescope To Fit in Shroud

8-meter Conventional Deployment



10-meter Robotic Assembly

Figure 3a -- Top View
Detail of Primary Mirror Segment
Mounted to its Stewart Platform

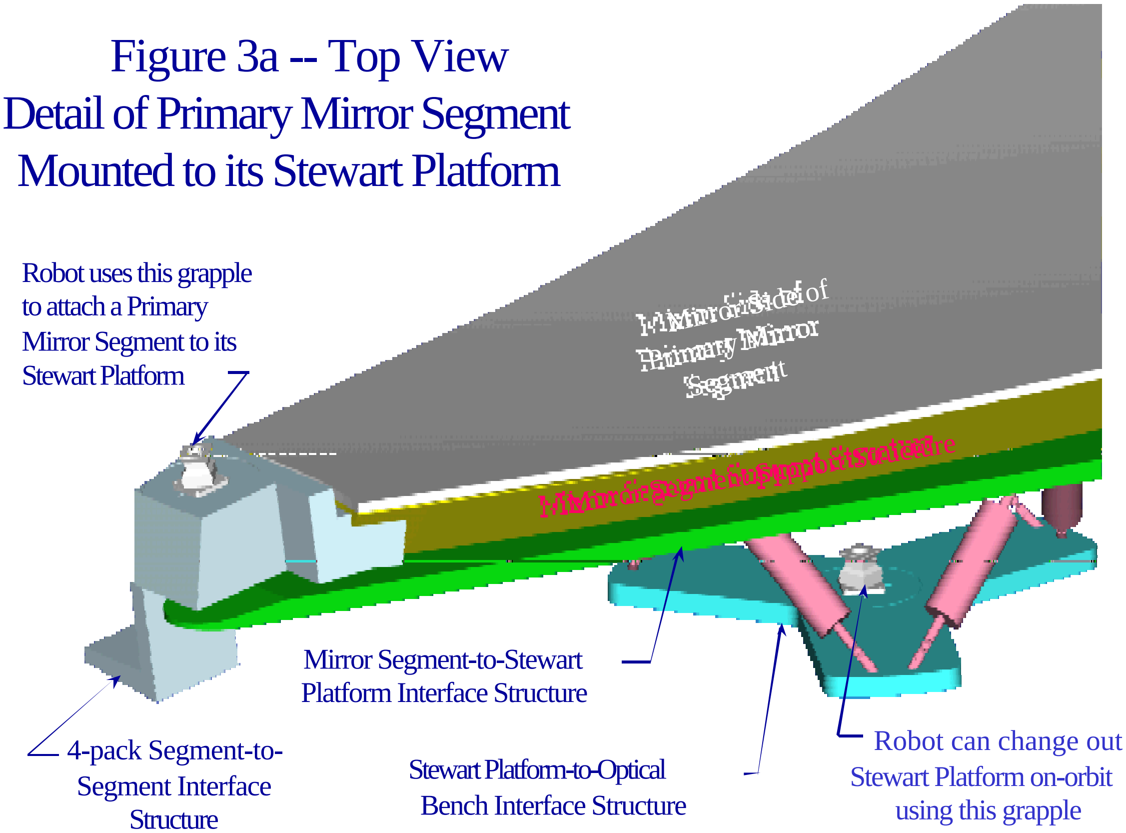


Fig 3b -- Bottom View

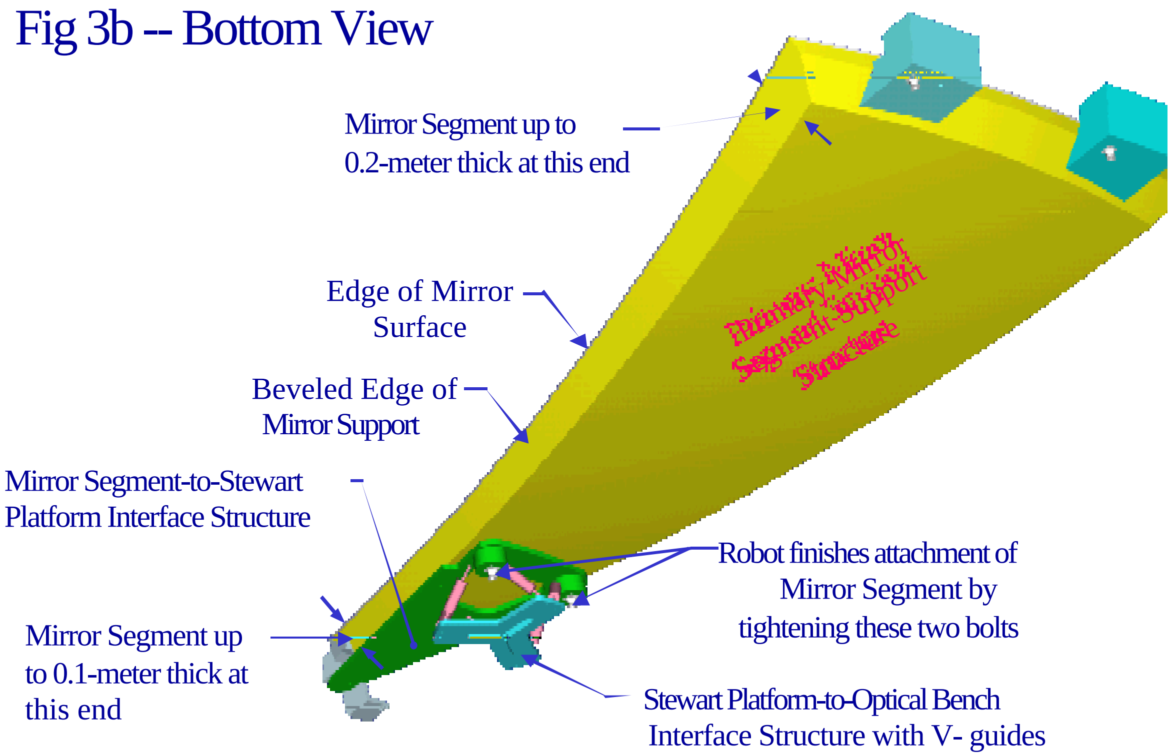


Figure 4 – Primary Mirror Segments in 4-packs

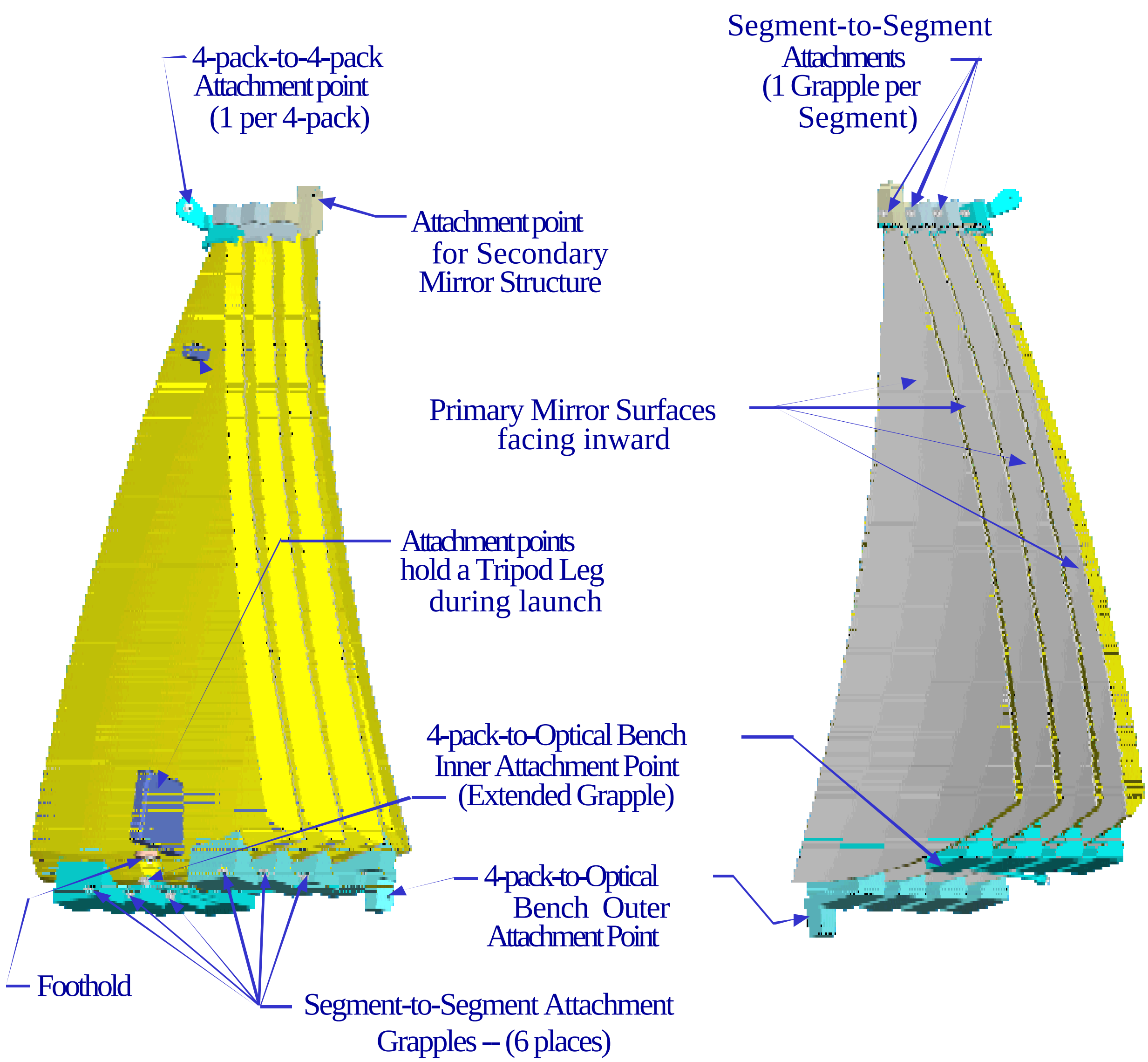


Fig 5 – Detail of Stowed Secondary Mirror

(Secondary Baffle and Labyrinth Seal not shown)

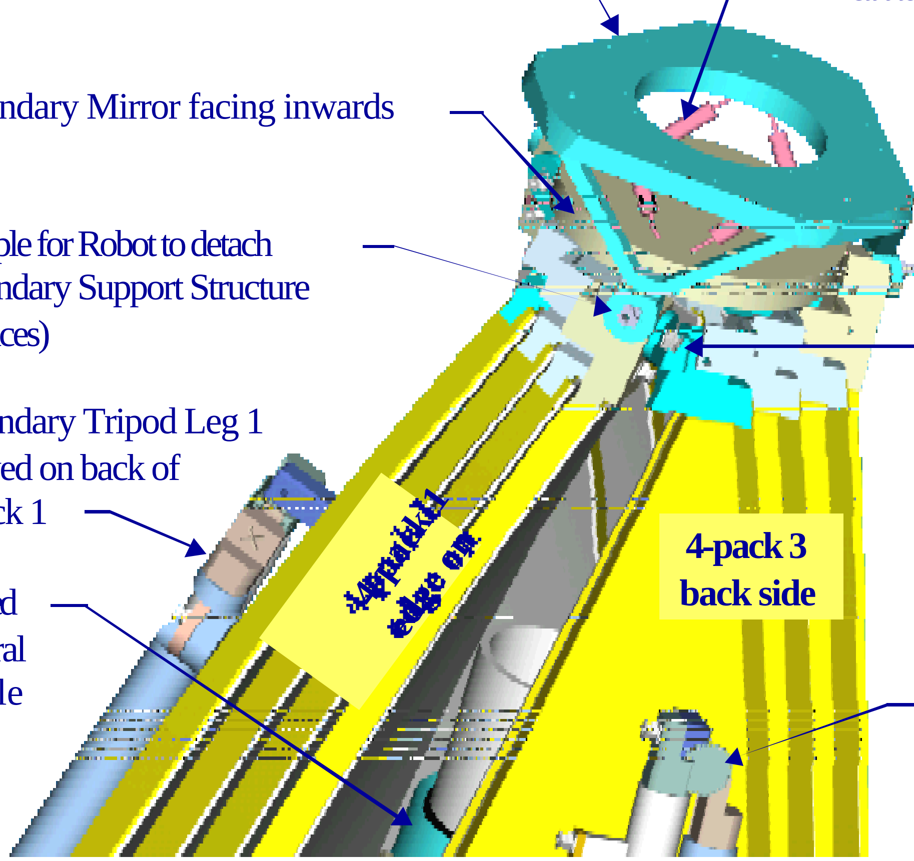


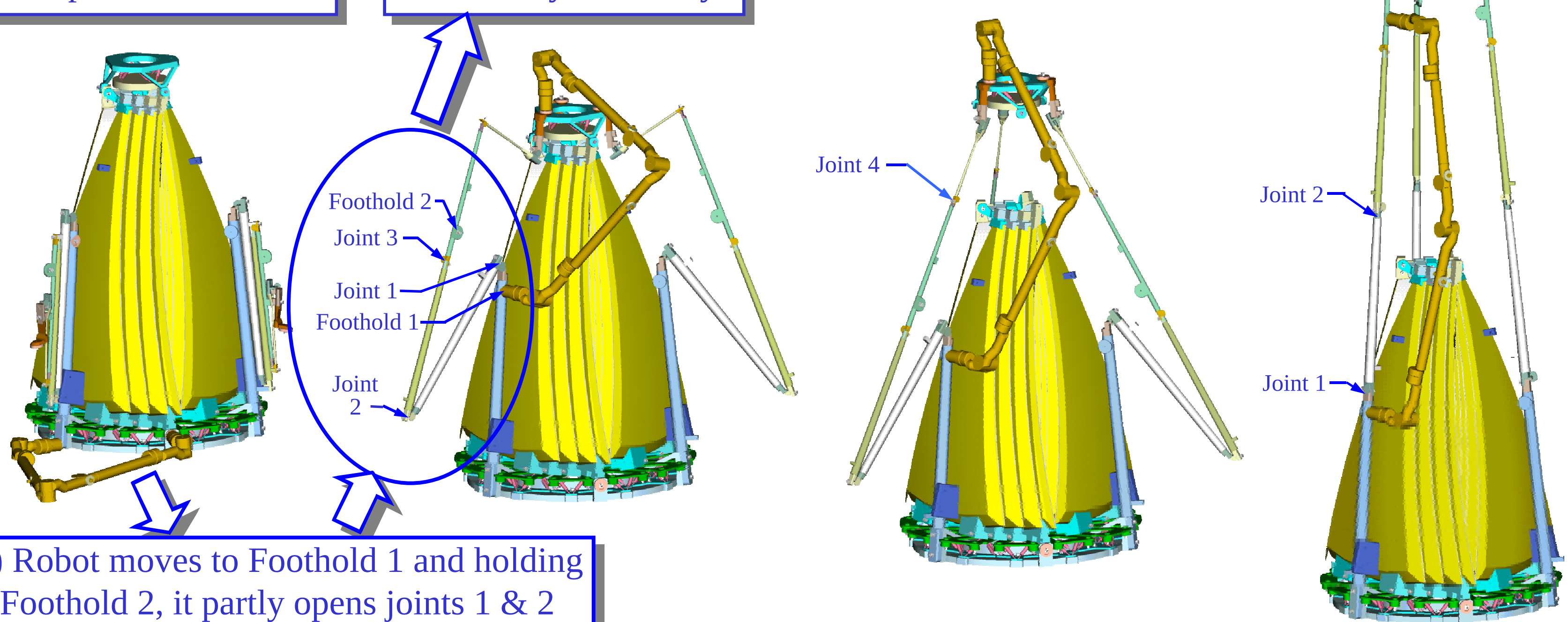
Fig. 6 -- Robot Assembly of Secondary Mirror

1) Robot unbolts 5 hinge joints then assembles a Tripod Leg onto Optical Bench

3) Holding Foothold 3, Robot attaches Tripod Legs to top of Secondary Assembly

4) Robot Lifts Secondary Assembly, Opens, & Locks Tripod Leg Joint 4

5) Holding Foothold 2, Robot fully opens and locks joints 1, 2, & 5



2) Robot moves to Foothold 1 and holding Foothold 2, it partly opens joints 1 & 2 and fully opens and locks joint 3

Fig. 7 -- Robot Repositions a 4-pack in Five Steps

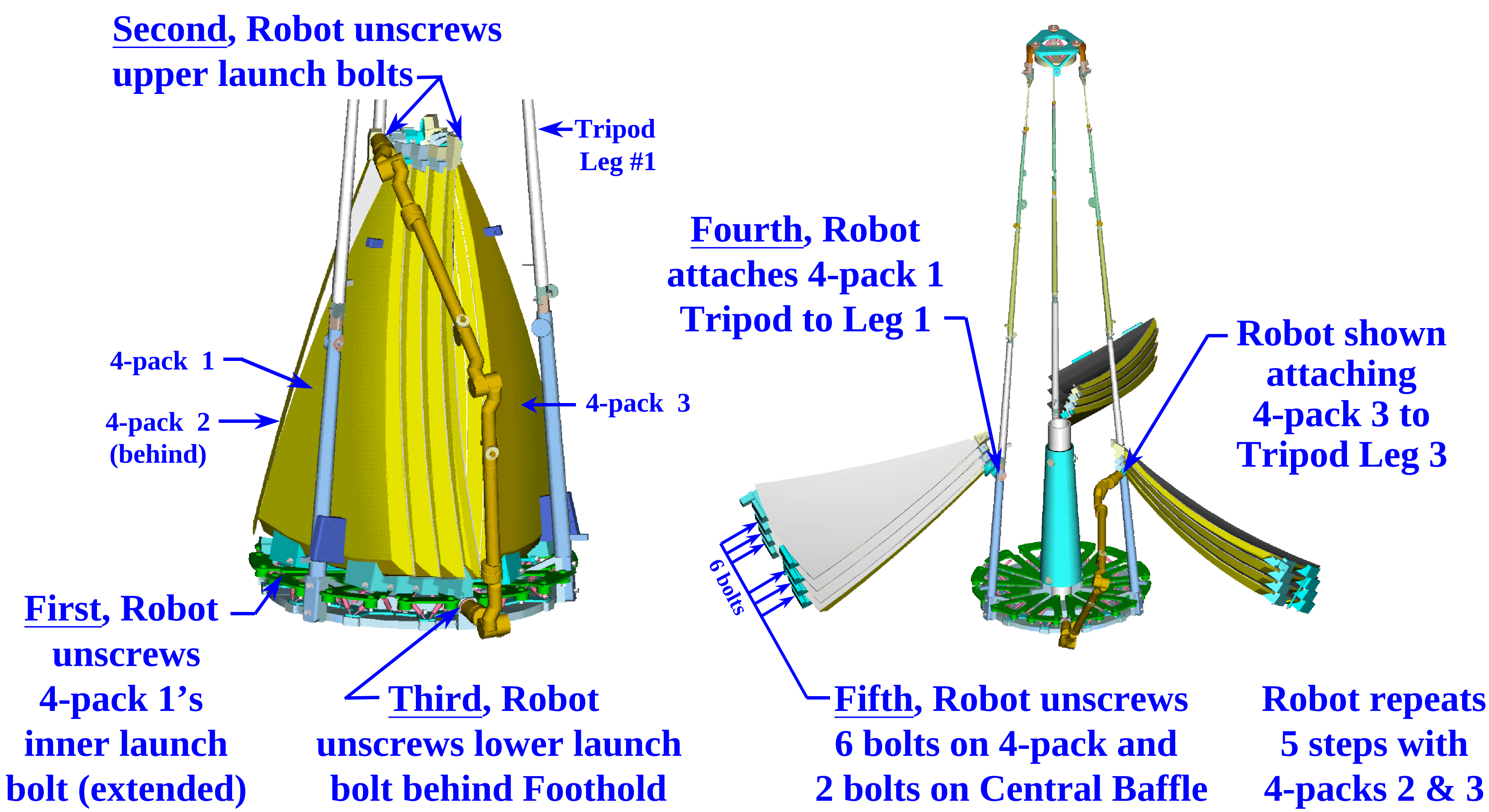
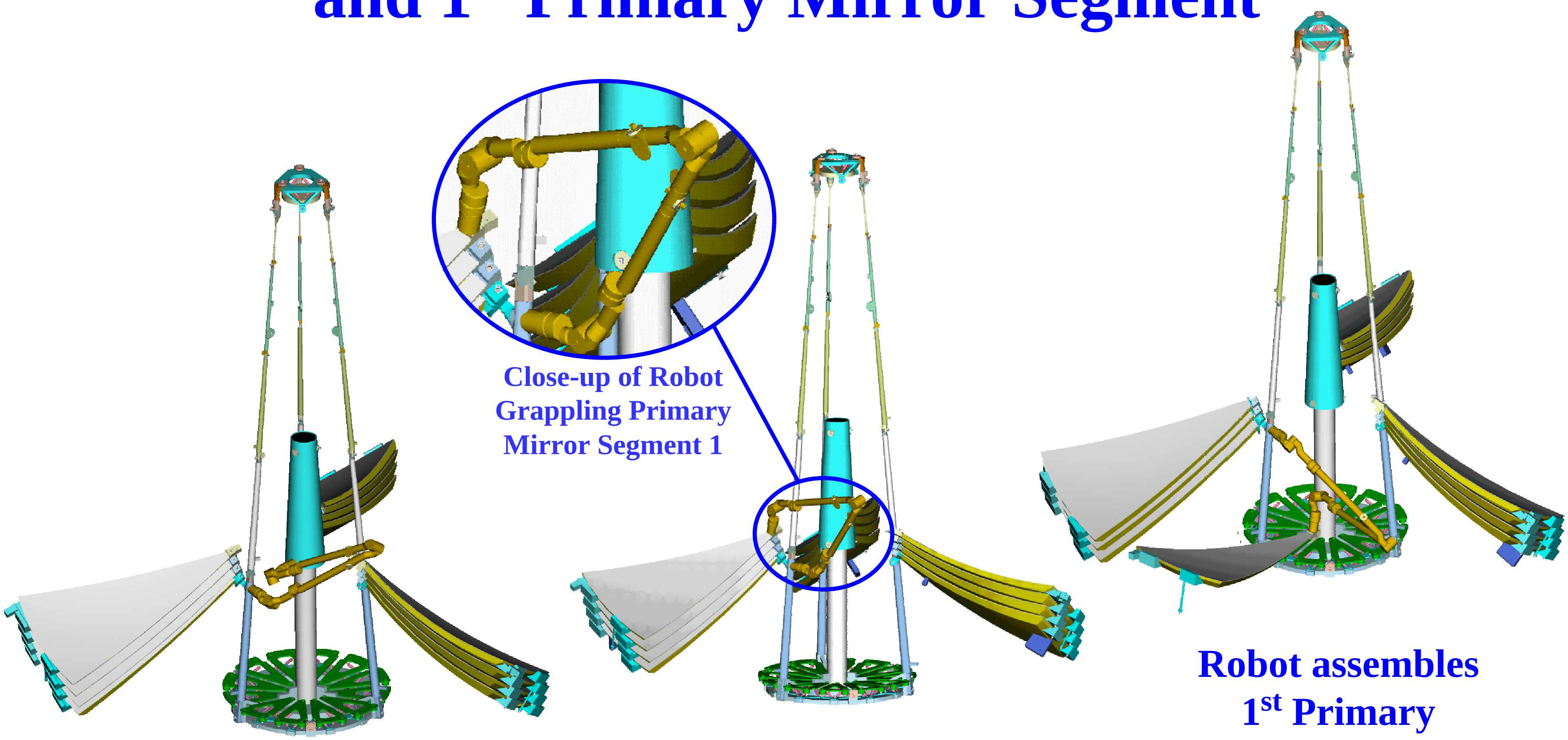


Figure 8 -- Robot Assembles Central Baffle and 1st Primary Mirror Segment



Robot changes Foothold and assembles Central Baffle

Robot detaches Primary Mirror Segment from 4-pack 1

Robot assembles 1st Primary Mirror Segment to its Stewart Platform

Figure 9 -- Robot Assembles 3rd and 4th Primary Mirror Segments

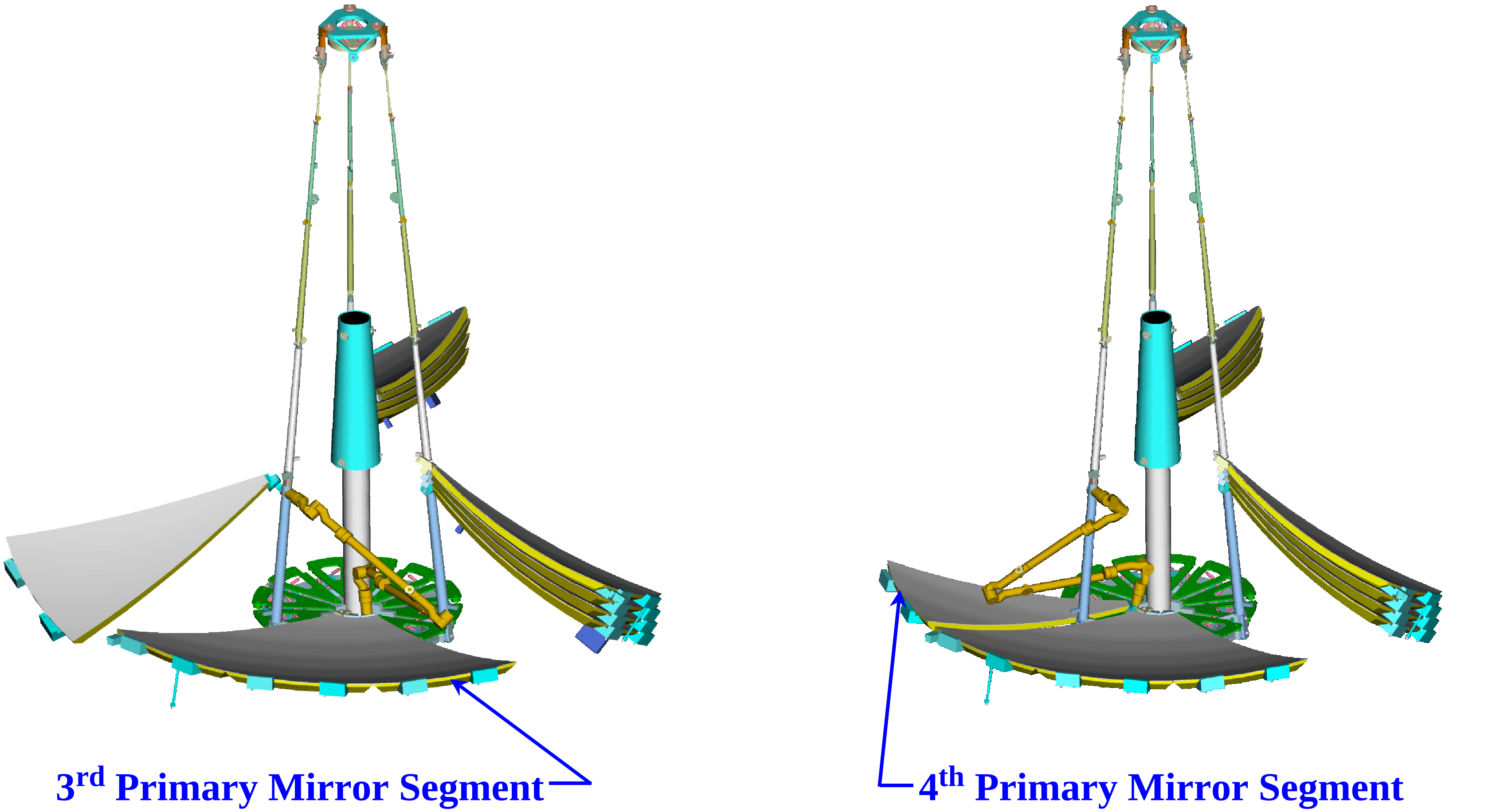


Fig 10 -- Telescope Completely Assembled, Robot Moves to Back of Primary Mirror