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RENDEZVOUS FIDUCIAL IMPLEMENTATION IN A SPACE VEHICLE LIFE CYCLE

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Rendezvous and capture of legacy satellites is significantly more challenging than rendezvous and capture of satellites prepared with servicing interfaces. Rendezvous fiducial markers (or fiducials) are a low cost, low mass, simple but effective tool to bridge the gap between legacy and prepared satellites. This paper presents the motivation for rendezvous fiducials as well as analysis demonstrating the improvement in state estimation accuracy with fiducials on the client satellite or space object. Included herein is a review of the life cycle of rendezvous fiducials such as the incorporation into a space vehicle design and photo documentation of the pre-launch installation. Answers to key implementation questions are answered: How many fiducials? Where should they be placed? What does the eventual servicer need to know? NASA case studies from the recently launched James Webb Space Telescope and in-design Nancy Grace Roman Space Telescope are included for illustration.

INTRODUCTION

In-space rendezvous is a process that brings two bodies together in orbit. Typically, and specific to this paper, there is one space vehicle that actively maneuvers to a second vehicle that is not maneuvering. The naming convention of *servicer spacecraft* for the maneuvering vehicle and *client space object* for the non-maneuvering vehicle is used herein[1]. For simplicity this paper denotes rendezvous as the relative ranges from 30 meters to the relative state necessary for client space object capture by the servicer spacecraft. There are numerous applications for in-space rendezvous including refueling, servicing, relocation, and disposal. These applications are enabling for future missions and space architectures[2].

Rendezvous, and more generally any servicing activity, can either be prepared or unprepared based on whether the client has features or functions that aid the servicer spacecraft. The complexity of servicing aids ranges from very low to challenging. Figure 1 provides types of aids sorted by complexity for the client space object to implement, dubbed the Servicing Spectrum[3]. The Servicing Spectrum includes servicing activities of relevance to current and future missions including Rendezvous, Capture, Refueling, and Spacecraft bus module and Instrument module changeouts. The left most column provides the aids applicable to Rendezvous. This paper focuses on the least complex aids: visual fiducials and photo documentation. Visual fiducials are typically flexible aluminum decals with machine vision markings that can dramatically improve serviceability of future spacecraft.

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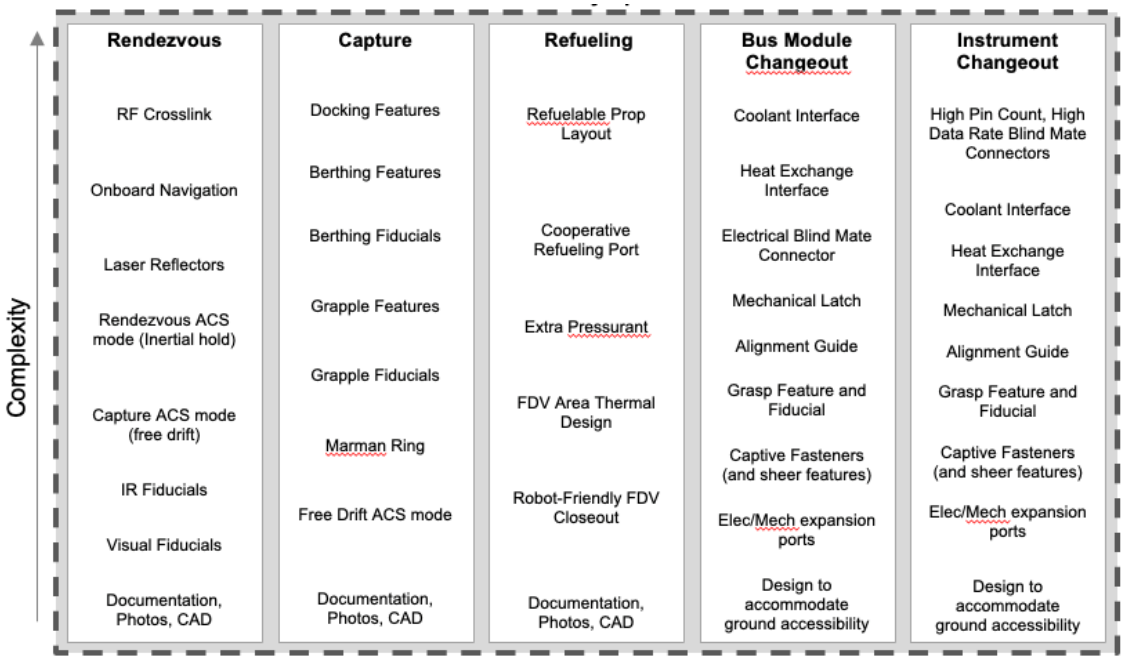


Figure 1. Servicing Spectrum

The term fiducial can describe any visual feature that is designed to enable autonomous detection. A single fiducial can be used to identify an object and its six degree of freedom (6DOF) relative pose or states. Multiple fiducials on the same body can be used to improve the estimation domain and accuracy of a body. Unique identifying characteristics are typically employed when multiple fiducials are used together. Fiducials have many applications beyond in-space rendezvous including augmented reality and robotics. Examples of visual fiducials provided in Figure 2 are the ARToolkit[4,5], ARTag[6], and AprilTag[7,8] fiducials.



Figure 2. Samples of visual fiducial: ARToolkit (left), ARTag (middle), AprilTag (right)

The AprilTag is the preferred fiducial by NASA's Exploration and In-space Services (NExIS) Projects Division due to its accuracy and detection rate, especially in the context of varying lighting conditions and occlusions. The AprilTag is the fiducial type used herein. The fiducials are manufactured by MetalPhoto of Cincinnati (MPC). Typical fiducials are 0.005" aluminum 1100 with a proprietary anodized coating that seals the AprilTag graphic within the anodic layer. The manufacturer can add mounting holes or an adhesive layer. Thicker fiducials can be produced if a stiffer design is desired.

The Rendezvous aids in the Servicing Spectrum share a common purpose to improve the servicer spacecraft's estimate of the client's 6 degree of freedom (6DOF) state regardless of the complexity of the rendezvous aids. The servicer spacecraft utilizes its estimate of the client's 6DOF states to determine how it will maneuver to the client space object. Without rendezvous aids a

servicer spacecraft is forced to determine the 6DOF state based on the client space object's natural features (e.g., geometry, reflectivity, etc). Algorithms to estimate the client space object state are an active area of development. These algorithms are computationally expensive, difficult to verify, and challenging to make robust. The Rendezvous aids address each of these challenges by simplifying the feature identification and correlation necessary to estimate the client's 6DOF state.

Space vehicle designers, compelled with the understanding that the addition of visual fiducials will reduce risk for a future servicing, must determine how to incorporate fiducials into their design. Inclusion of the fiducials in the space vehicle design early can increase the value to the future servicer spacecraft by ensuring that the fiducials are visible from the servicer spacecraft's approach corridor and there are adequate quantity, size, and spatial distribution. However, fiducials can be added very late in the vehicle integration flow since the most common method of installation (i.e., adhesion) and verification data (i.e., photo documentation) is minimal.

This paper provides the process for incorporating rendezvous fiducials into the prospective client space object design. Section 2 identifies key questions and provides a process to determine the answers. Examples of early and late inclusion of fiducials in a vehicle's design are provided for illustration. The disadvantage of late additions is that the maturity of the vehicle design can limit the locations for fiducials that will be helpful to the future servicer spacecraft. Early inclusion results in improved fiducial placement with minimal effort from the vehicle designers.

Section 3 provides a case study of an early adopter of fiducials into space vehicle design. Section 4 provides a case study of a late adopter of fiducials into the vehicle design. Section 5 draws comparison between the early and late adopters and includes lessons learned from both.

PROCESS TO INCLUDE RENDEZVOUS FIDUCIALS IN THE VEHICLE DESIGN

Two recognizable space vehicles depicted in Figure 3 are used to illustrate the differences between early and late inclusion of fiducials in a vehicle design. The first vehicle is the James Webb Space Telescope (JWST). JWST is an infrared space telescope developed by Northrop Grumman under the management of NASA's Goddard Space Flight Center (GSFC). NASA decided very late in the development that adding fiducials would be a prudent low impact risk mitigation for a highly unlikely future servicing mission to JWST. The second vehicle is the Nancy Grace Roman Space Telescope (Roman). Roman is a visible and near-infrared space telescope developed by NASA's GSFC. Roman had a requirement to be serviceable from early in the design development. Roman had visible fiducials included in its design before PDR, whereas the James Webb Space Telescope (JWST) had visible fiducials added to the design long after CDR.

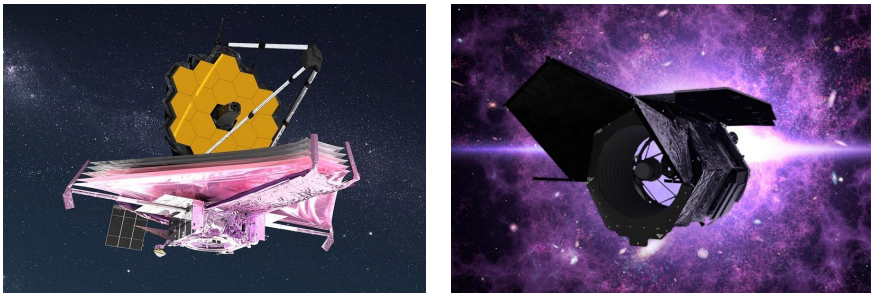


Figure 3. James Webb Space Telescope (right), Nancy Grace Roman Space Telescope (right)

The key questions that need to be answered to determine the fiducial design for a space vehicle are:

- What type of fiducial will be used?
- What is the fiducial size?
- How many fiducials?
- Where will the fiducials be located?
- How will the fiducials be attached to the client?
- How will the installed fiducial location be determined?

The process to answer these questions is provided in Figure 4. The process is presented as a serial flow which starts with identification of the point on the prospective client space object that the servicer spacecraft will use to capture the client space object. The point should be rigid relative to the primary structure of the vehicle since it will be the transmission point of the internal loads between the servicer spacecraft and client space object once grappled. Additionally, the point should be external accessible and free from clutter. The point can be a grapple fixture, an item specifically designed for a hypothetical servicer spacecrafts grapple interface. Vehicles without a grapple fixture will likely identify the launch interface or other connection to the primary vehicle structure as the grapple location.

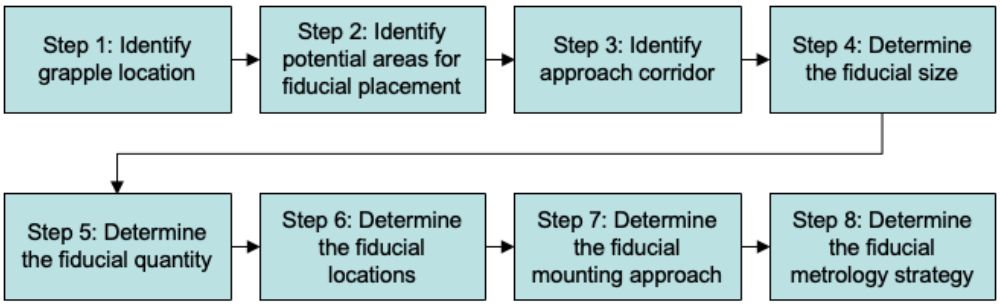


Figure 4. Vehicle Fiducial Design Process

Step 1 examples: The Roman design included a grapple fixture as an element of its serviceability design. The identification of the grapple location was therefore a given. Unlike Roman, the JWST did not have a requirement to be serviceable and did not include a grapple fixture. Without a grapple fixture the JWST launch interface adapter was assumed to be the grapple location for a hypothetical servicer.

With the grapple location identified, the next step is to determine potential areas for the fiducials to be placed. The fiducials should be mounted on a rigid surface that is stable relative to the grapple location. This is readily achievable for designs where the fiducial has been included since the early stages. Designs that add fiducials late in development are challenged to find available rigid surfaces that are not covered with a flexible multi-layer insulation (MLI) blanket or occulted from the approach corridor.

The next step is determining the approach corridor in the client body frame that the servicer spacecraft will take to get to the grapple point of the client space object. The approach corridor will typically be along a principal body axis of the client space object that is normal to the surface with the grapple location. This nominal approach corridor must be evaluated in the context of the fiducial placement to ensure the fiducials are not occlude by client space object features from the servicer spacecraft in the approach corridor.

Step 2&3 examples: Figure 6 shows a Computer Aided Design (CAD) rendering of the aft end of Roman including the launch interface adapter and the grapple fixture. The Roman designers denoted a primary area near the grapple fixture for fiducials that was suitable to the vehicle design.

In Figure 6 this area contains five fiducials in an "X" pattern. Unfortunately, this area was partially occluded by the launch interface adapter when viewed from the axis normal to the aft end of the vehicle. Figure 9 depicts the servicer approach corridor which was tilted 15 degrees from the aft end normal to mitigates the primary fiducial area occlusion. The resulting view of Roman from the approach corridor is shown in Figure 7.

The JWST is an example of late adoption where open rigid surfaces were not available, nor could the system tolerate even minor changes to the mechanical or thermal design. Vehicle designers identified areas on the MLI around the grapple point that were suitable for fiducials to be bonded to the outer layer of the MLI. Unfortunately, MLI is not rigid so the fiducials can deform and move relative to the vehicle structure which can reduce the state estimate accuracy deduced from the fiducials. That said, it was ultimately concluded that fiducials on the MLI were better than no fiducials at all.

Step 4-6 examples: The process and effort for next three steps, i.e., establish the fiducial size, quantity, and final locations, can vary significantly. This paper illustrates the two extremes: subject matter judgement versus a client specific dedicated study. The Roman funded a dedicated study to identify the fiducial size, quantity, and locations based on an optimal parameter space search. The results were seven fiducials that were 100 mm square with five on the primary fiducial area and one fiducial on each of two umbilical towers on the aft deck. The subsequent section provides the details of the study.

By contrast the JWST design relied on subject matter judgement from NASA's Exploration and In-space Services Projects Division to determine the fiducial size, quantity, and locations. There was no study of the fiducial size, location, or quantity conducted due to funding and schedule constraints. The fiducials used were 50 mm which NExIS had on hand from previous technology demonstration missions to the International Space Station (ISS)[9]. The fiducials were placed near the launch interface adapter as shown in Figure 5. The fiducials were to be bonded to the outer layer of the MLI since a rigid structure or surface was not available due to the maturity of the vehicle design. Six fiducials in total, three inside the launch interface adapter and three outside were added to the vehicle design as shown in Figure 5.

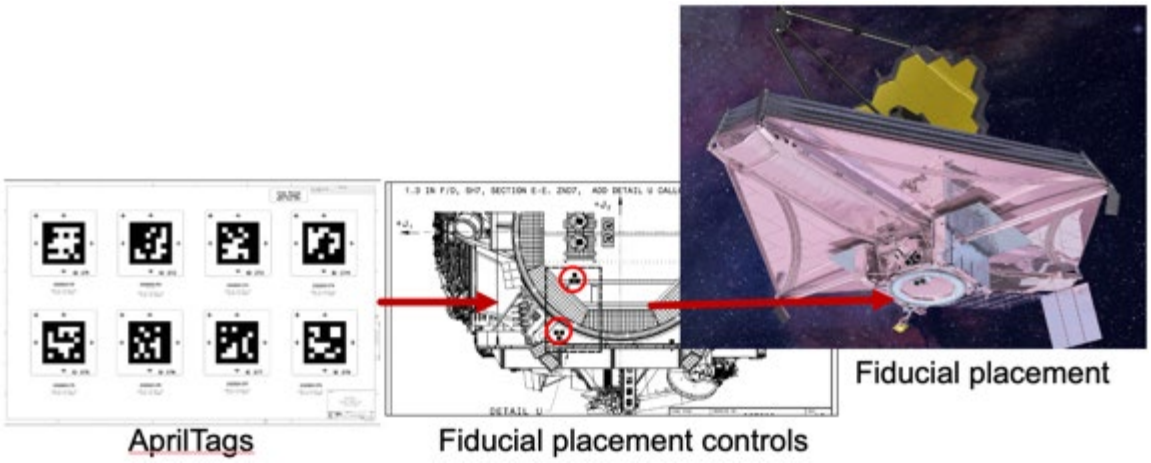


Figure 5. JWST fiducial placement

Fiducials are most practically bonded directly to a surface. The more desired strategy is mounting the fiducial to rigid structure.

Step 7 examples: Roman is an example of early adoption where the design bonded the fiducials on aluminum plates that were rigidly attached to the vehicle structure. The aluminum plates that hold the fiducials are low mass and affixed to the umbilical towers and aft deck in a way that was convenient to the vehicle designer. Each Roman fiducial is coated with indium tin oxide (ITO) to mitigate surface charging of the anodized aluminum substrate of the AprilTag. The perimeter of each fiducial is covered by an aluminum picture frame that serves as a secondary restraint in case of bonding failure The fiducials were grounded via a CHO-SEAL gasket between the fiducial and the picture frame. The JWST fiducials were bonded directly to the outer layer of MLI as previously noted. JWST designers elected to not use ITO coated fiducials.

The last step in the process is determining the process that will be used to locate the as-installed fiducials. The critical information needed by the servicer spacecraft is the location of the fiducial relative to the grapple fixture. The AprilTag system resolves the fiducial reference frame as shown in Figure 10 however the pose estimator of the multi-fiducial system can use the corners of each fiducial and disregard the fiducial frame rotation. In this way the impact of localized deformation or rotations of the fiducial can be mitigated.

There are two primary methods to establish the pre-launch locations of the fiducials relative to the grapple location. Either use metrology tools such as laser radar to directly measure or use photogrammetry indirectly measure the as-installed fiducials and the grapple location.

Step 8 examples: Late adopters like JWST will rely on photogrammetry to determine the as-installed locations of the fiducial. Photogrammetry uses images of the fiducials in the context of other rigid features on the vehicle to determine the fiducial locations in the vehicle structural frame. The process requires photos of the vehicle and a CAD model or drawing that provides the rigid features from the photos. The penultimate section of this paper describes the photogrammetry processing used to determine the as-installed fiducial location on JWST.

Early adopters like Roman can include metrology with negligible effort. The mounting plates for the fiducials and grapple fixture mounting include holes for metrology tooling balls to locate the as-installed locations relative to the vehicle structural frame. Adding a hole to simple aluminum plate at design time is trivial effort. Each fiducial will be located on its mounting plate before the mounting plates are installed on the vehicle. This provides the necessary information to determine the fiducial location relative to the grapple fixture.

The process described herein has been used to add rendezvous fiducials to the design of many potential client vehicles. The next two sections detail the Roman design study and the JWST photogrammetry processing.

ROMAN SPACE TELESCOPE FIDUCIAL STUDY

Space vehicle designers set out to answer the key questions above. NExIS Projects Division and Roman designers used the process outlined in Figure 4 to find a fiducial design that was suitable for both Roman and a future servicer spacecraft.

Sensitivity of Servicer Spacecraft FOV vs Fiducial Size and Pattern Size

To estimate the sensitivity of the system parameters, a virtual simulation study was performed to assess the accuracy of a typical computer vision-based pose estimation system intended to be used on Roman. The main components of the pose estimation system are a monocular camera and a set of fiducials. As previously noted, AprilTag fiducials are used in this analysis. A virtual simulator was used to study several parameters of the camera and fiducials of the pose estimation system. The virtual simulator was implemented as a C++ application that uses the OpenGL library for graphic generation. It uses CAD models of Roman, adds the AprilTag fiducials to them and then

generates camera views according to the given simulation parameters (see Figure 6). Finally, the camera views are converted to OpenCV images and given to the pose estimation system. The parameters presented in Table 1 are considered in this study. This study assumes ideal illumination conditions.

Table 1 Simulation Parameters

Camera resolution:	2048 x 2048 pix
Camera Field of View:	4 to 20 deg, 2 deg increments (9)
Fiducial size (black border):	32 to 64 mm, 4 mm increments (9)
Camera-Roman distance:	2 m to 30 m, 1m increments (29)
x-rotations:	-5 to 5 deg, 5 deg increments (3)
y-rotations:	-4 to 4 deg, 4 deg increments (3)
z-rotations:	-4 to 4 deg, 4 deg increments (3)
Scenarios:	1 fiducial, 5 fiducials, 7 fiducials (thrusters), 7 fiducials (umbilical towers)

The pose estimation system detects the fiducial(s) on the OpenCV image. Using the corners of the detected fiducials, the pose is estimated with the OpenCV function cv::solvePnP(). One of the arguments of that function is the type of solver to use for finding the estimated pose. In this study the cv::SOLVEPNP_ITERATIVE option is used; it is an iterative method based on a Levenberg-Marquardt optimization. If the z-translation component of the estimated pose is negative (Roman should be in front of the camera), then the operation is repeated with the cv::SOLVEPNP_EPNP option. The 6DOF pose is given as a transformation matrix, which contains a three-by-three rotation matrix and a three-component vector that gives the location of the target frame.

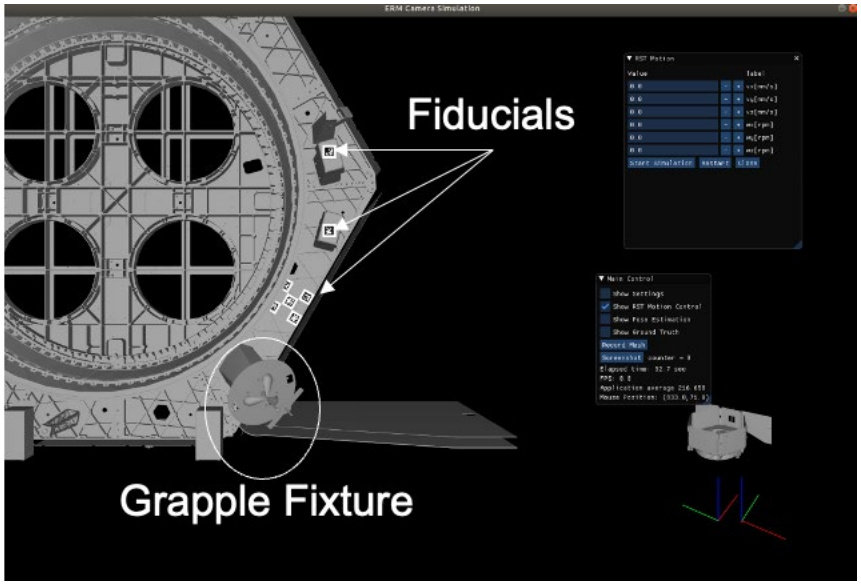
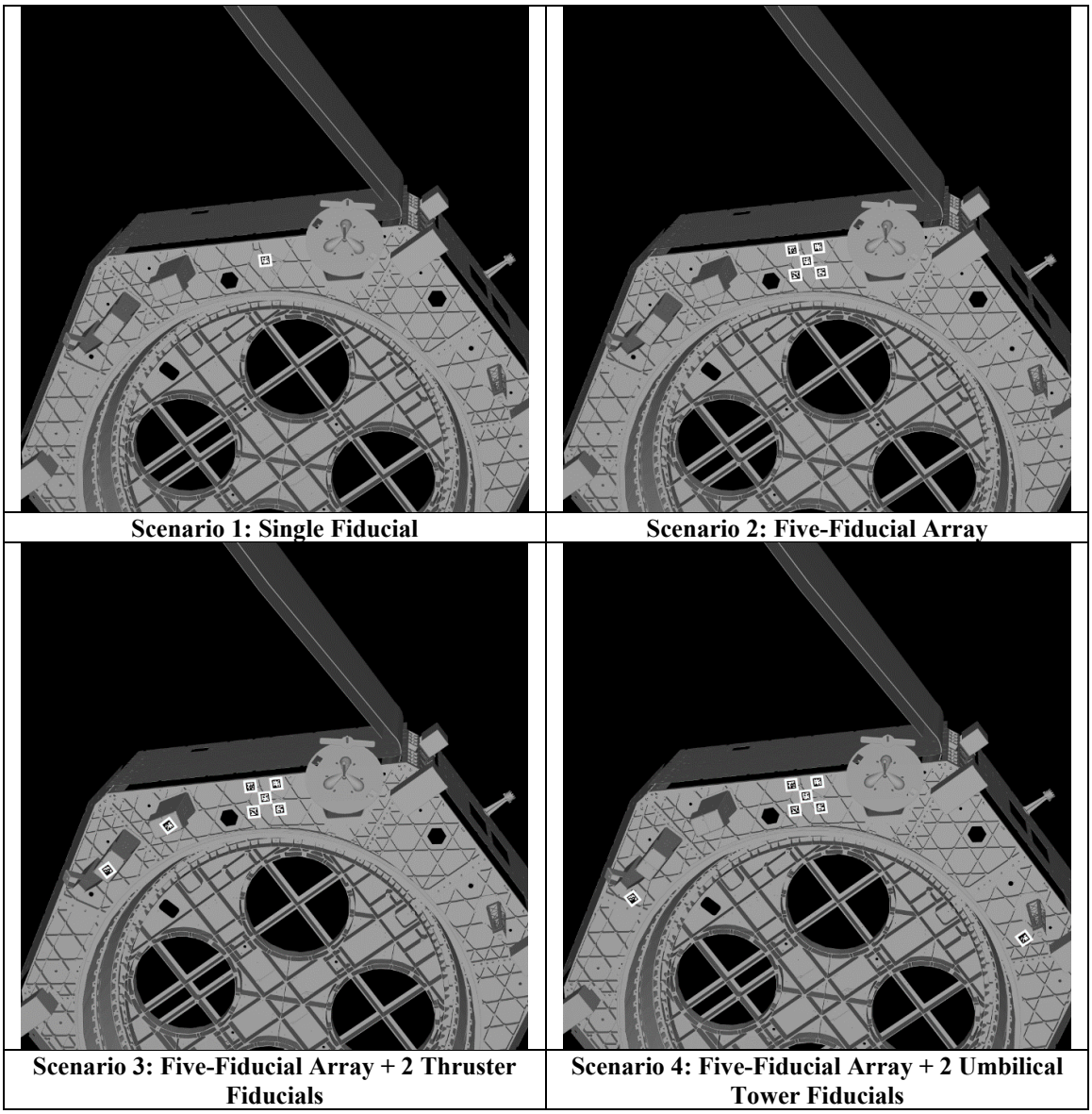


Figure 6 Graphical user interface of the virtual simulator

Simulation Scenarios

In this study four different simulation scenarios are considered; each one represents a different arrangement of the AprilTag fiducials. The different scenarios are presented in Figure 7 and described in the following sections.

For each scenario, different camera views are generated according to the fiducial size, camera field of view (FOV) and camera to Roman pose defined in Table 1. A configuration is defined by a given fiducial size and camera FOV. A total number of 63423 (9×9×29×3×3×3) images are generated for each scenario. For a given configuration there are 783 (29×3×3×3) camera to Roman poses. For a given configuration at a given distance there are 27 (3×3×3) camera to Roman orientations.



Scenario 1: Single Fiducial | **Scenario 2: Five-Fiducial Array**

Scenario 3: Five-Fiducial Array + 2 Thruster Fiducials | **Scenario 4: Five-Fiducial Array + 2 Umbilical Tower Fiducials**

Figure 7. Simulation scenarios

Scenario 1: Single Fiducial

In this scenario a single AprilTag fiducial is used and therefore it is a planar or 2D target. In this study several fiducial sizes are considered according to the values presented on Table 1. Note that the dimensions refer to the external black border of the fiducial (see Figure 8). The fiducial is located on the Roman aft end lower deck (approx. 40mm above it).

Scenario 2: Five-Fiducial Array

In this scenario five AprilTag fiducial are used. There is a central fiducial and four fiducials on each corner of a 300mm x 300mm square (see Figure 8). The size of the fiducials considered in this study varies according to the values presented on Table 1, but the distribution of the fiducial is always the same. The five fiducials are located on the Roman aft end lower deck (approx. 40mm above it). Since the fiducials are located in the same plane, it is a planar or 2D target.

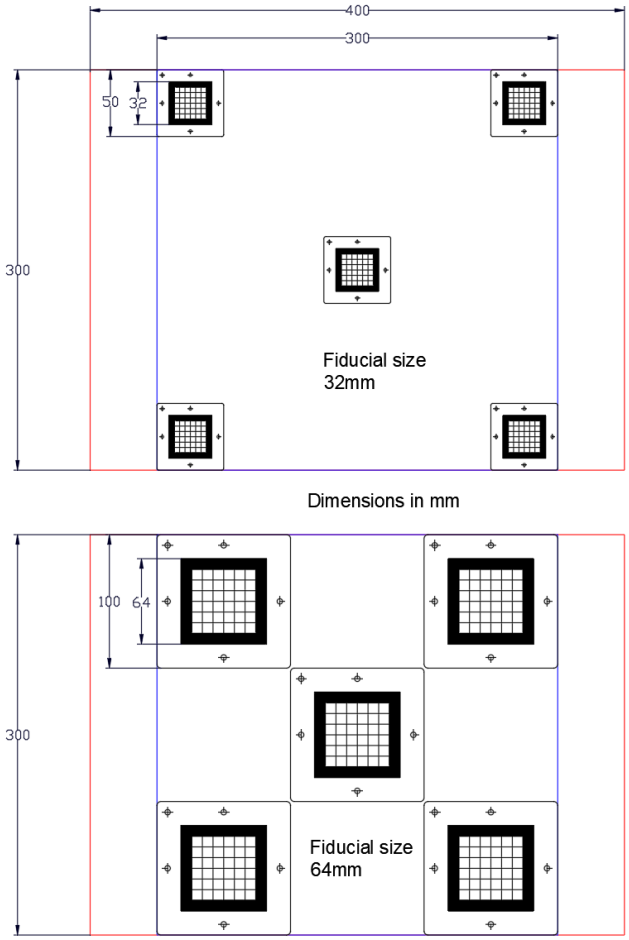


Figure 8. Five-fiducial array dimensions (top: smallest fiducial size, bottom: largest fiducial size)

Scenario 3: Five-Fiducial Array and Two Thruster Fiducials

This scenario has the same five-fiducial array of Scenario 2 and two fiducials located near the Roman thrusters. The fiducials located on the Roman thrusters are 533mm away (along the fiducial z-axis, see Figure 10) from the five-fiducial array.

Scenario 4: Five-Fiducial Array and Two Umbilical Tower Fiducials

This scenario has the same five-fiducial array of Scenario 2 and two fiducials located on the Roman umbilical tower. The fiducials located on the umbilical towers are 456mm away (along the fiducial z-axis, see Figure 10) from the five-fiducial array.

During the simulation the camera orientation is held constant as defined in Figure 9. The camera is looking at the central fiducial of the five-fiducial array (or the single fiducial) when there are no rotations on the Roman (*rx=ry=rz=0*), and the angle between the camera focal axis and the Roman longitudinal axis is 15 deg. The camera location keeps an approach path of 15 deg as presented in Figure 9. The Roman rotations are performed in its body fixed frame (see Figure 10).

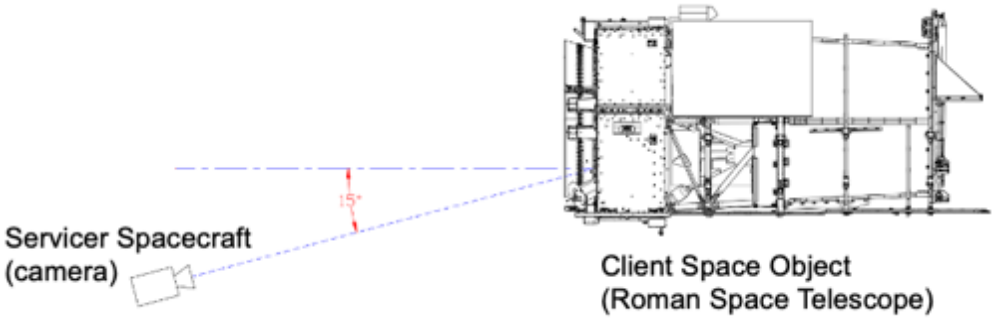


Figure 9. Servicer Spacecraft Camera orientation and approach path

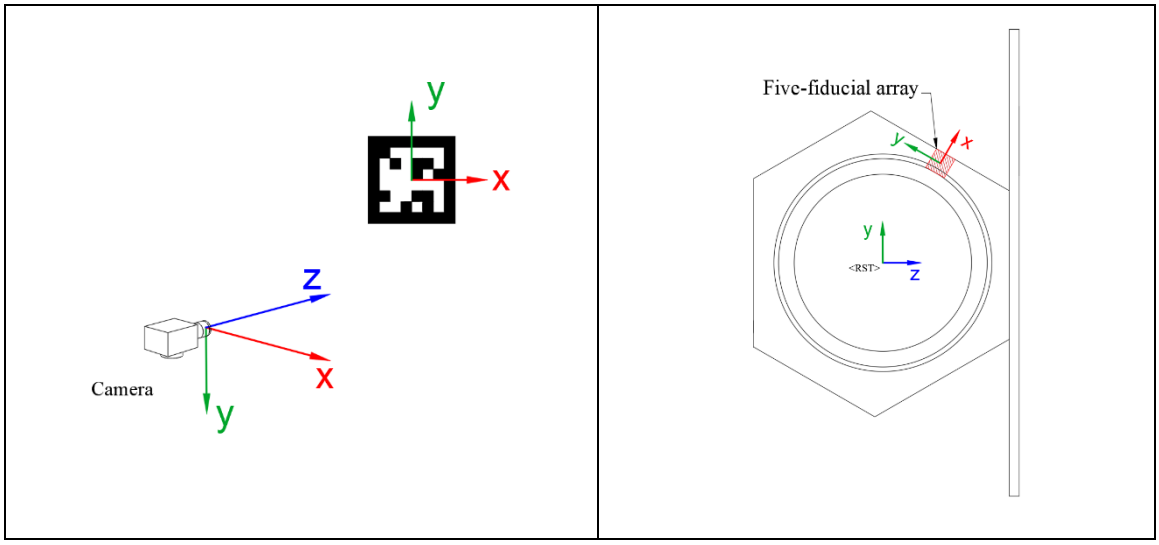


Figure 10. Reference frames

Pose Estimation Error

The 6DOF pose estimation error is defined as the transformation matrix of the estimated camera frame with respect to the actual or truth frame (see T_{error} in Figure 11). In this study the actual pose of the fiducials with respect to the camera frame is known. From Figure 11 it can be seen that,

$$^{F}T_{C,Est} = {}^{F}T_{C,Tru}T_{error}$$

Solving for T_{error},

$$T_{error} = {}^{F}T_{C,Tru}^{-1}\,{}^{F}T_{C,Est}$$

Using the more common transformation matrix of ${}^{C}T_{F}$,

$$T_{error} = {}^{C}T_{F,Tru}\,{}^{C}T_{F,Est}^{-1}$$

The rotation component of the transformation matrix T_{error} is then converted to Euler angles: rx_{error}, ry_{error}, and rz_{error}. The translation components of T_{error} are defined as the translation error components,

$$x_{error} = T_{error}(1,4)$$

$$y_{error} = T_{error}(2,4)$$

$$z_{error} = T_{error}(3,4)$$

The lateral rotation error is defined as,

$$rxy_{error} = \sqrt{rx_{error}^2 + ry_{error}^2}$$

And the lateral translation error is defined as,

$$xy_{error} = \sqrt{x_{error}^2 + y_{error}^2}$$

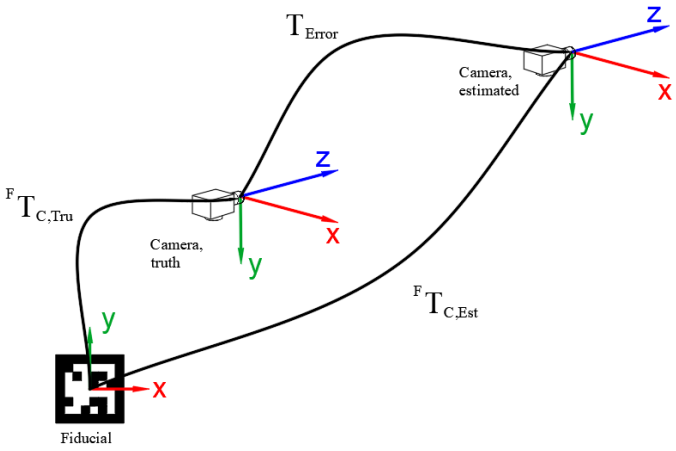


Figure 11. Pose estimation error

Pose Estimation Error Requirements

The pose estimation error requirements depend on the camera to Roman distance, and they are defined as follows, the x,y translation error: orthogonal to the z-axis to within 4% of the true range, the z-translation error: z-axis to within 4% of the true range, the x,y-rotation error: the angle between the Client capture axis and the SP Z axis to within 20% of the true range plus 1.4 deg and the z-rotation error: the rotation about the Client capture axis within 20% of the true range plus 2.1 deg. The pose estimation error requirements are based on the OSAM-1 servicer spacecraft, which is preparing for a rendezvous mission to a legacy spacecraft.

Roman Sensitivity Results

This section shows the detectability and valid accuracy plots for each scenario. The detectability plot shows the percentage of cases, for each configuration, where at least one fiducial was detected. If a configuration has 100% detectability, it is represented as bright yellow spot in the detectability colormap, and it means that for that configuration the fiducial was always detected at each one of the 783 different camera to Roman poses used in the simulation. If there is one single case of no detection, then the detection percentage would be (783-1)/783 = 99.87%.

The valid accuracy plot shows the percentage of cases, for each configuration, that meet the accuracy requirements at each distance. When calculating the valid accuracy percentage, the cases are grouped according to the camera to Roman distance. There are 27 cases per distance, and 29 distances, but if one of those cases fails, then the detectability for that distance will fail. The percentage is calculated using the number of "valid" distances, if only one case fails then the valid accuracy would be calculated as (29-1)/29=96.55%.

Scenario 1: Single Fiducial

Figure 12 shows the detection percentage and valid accuracy plots for Scenario 1.

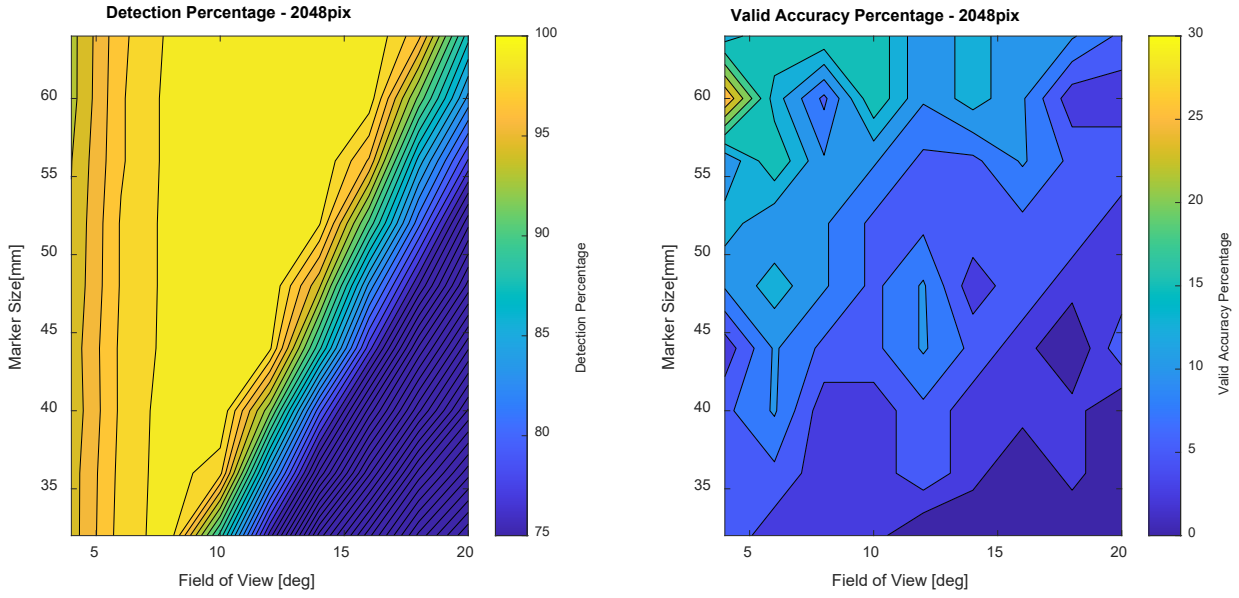


Figure 12. Scenario 1 results

Scenario 2: Five-Fiducial Array

Figure 13 shows the detection percentage and valid accuracy plots for Scenario 2.

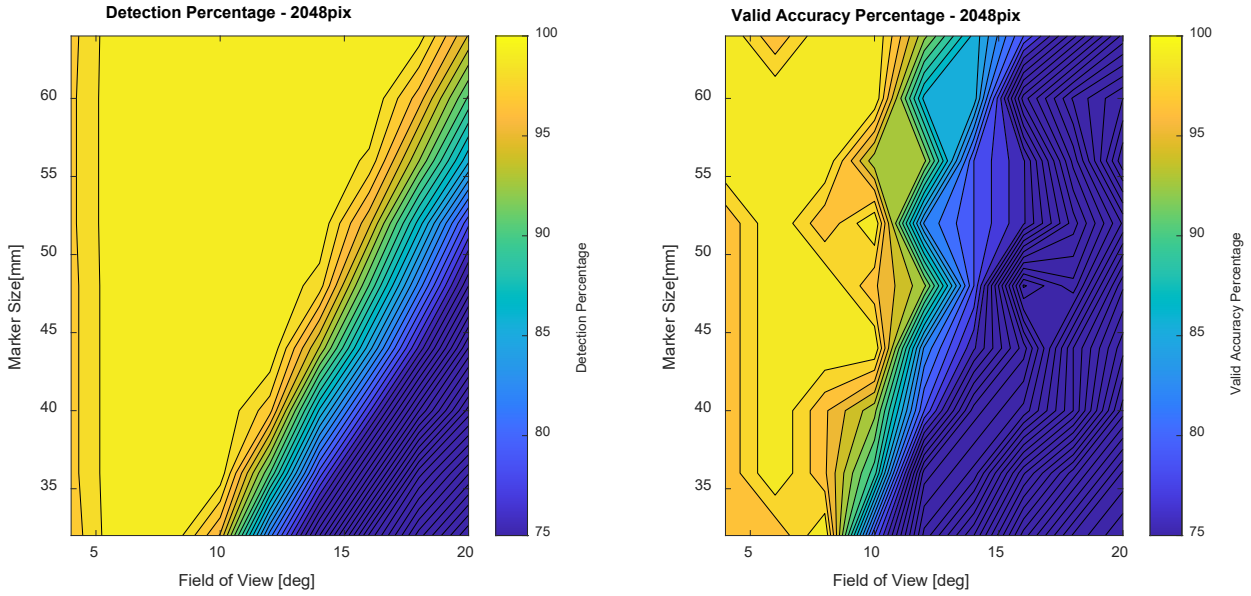


Figure 13. Scenario 2 results

Scenario 3: Five-Fiducial Array + 2 Thruster Fiducial

Figure 14 shows the detection percentage and valid accuracy plots for Scenario 3.

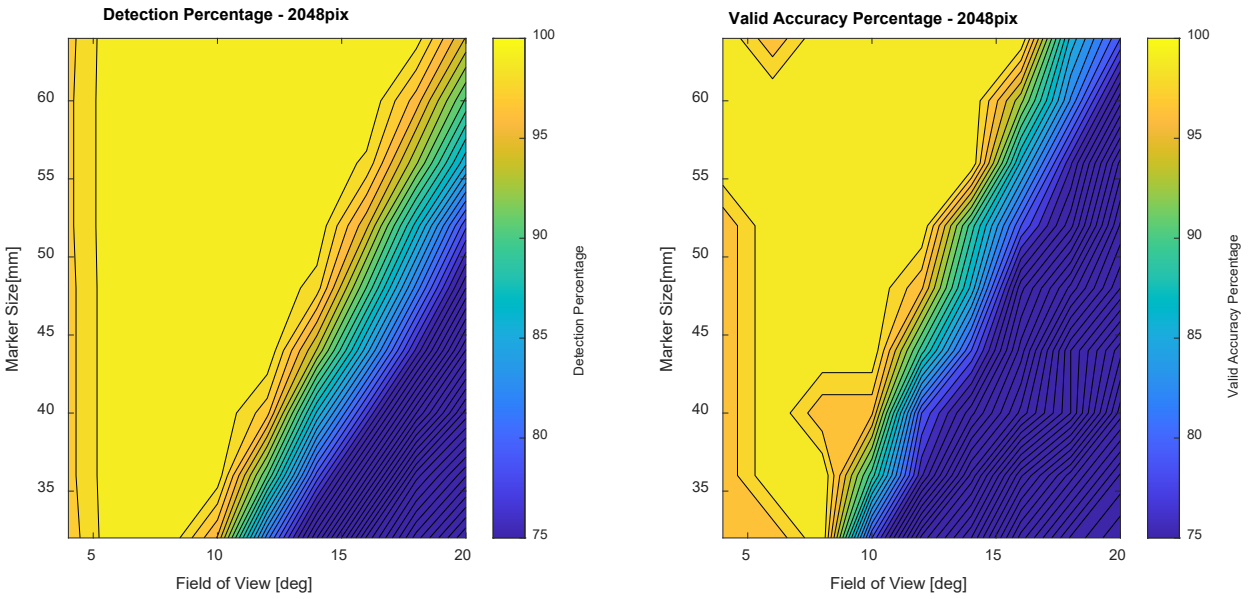


Figure 14. Scenario 3 results

Scenario 4: Five-Fiducial Array + 2 Umbilical Tower Fiducial

Figure 15 shows the detection percentage and valid accuracy plots for Scenario 4.

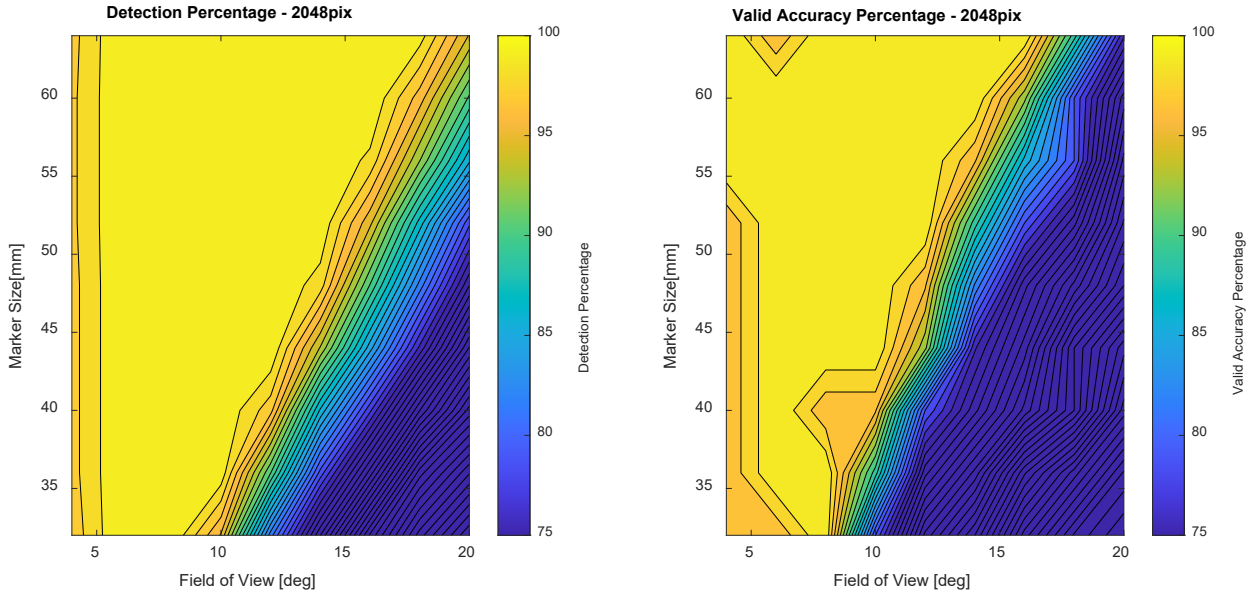


Figure 15. Scenario 4 results

Roman Sensitivity Study Conclusions

There are two trends revealed by the fiducial size and camera FOV sensitivity. Larger fiducial size increases detectability and accuracy while narrower camera FOV increases accuracy and long-range detectability. At the same time, a narrow camera FOV at close range reduces detectability since the fiducials can be out of the camera view.

The fiducial quantity and distribution sensitivity show expected results. Multiple fiducials increase detectability and accuracy. Larger spatial distribution needs large camera FOV to maintain detectability, else the fiducials can be out of the camera view. The accuracy is increased with the fiducials spread out over a larger area, which is analogous to having one very large fiducial.

There are two typical conditions when the system does not meet the required accuracy. The first condition is when using a narrow FOV at close range, in this case some of the fiducials are out of view, or partially out of view. The failure occurs on the lateral rotation error. The second condition is when using a wide FOV at long range, the failure usually occurs when less than seven fiducials are observed, or when the fiducials are concentrated on a small area and some of the fiducials appear too small on the image to be detected or they appear outside or partially outside of the camera view.

The pose estimation error exhibits the typical behavior of computer vision-based pose estimation systems: z-rotation error smaller than xy-rotation errors, xy-translation error smaller than z-translation errors and a bias in the z-translation error that increases with range, other errors have

approximately zero bias. The accuracy requirement that fails most frequently is the lateral rotation followed by the z-translation. The lateral translation requirement is usually satisfied.

The study recommendation is to implement the largest possible fiducial (64mm in this case, 100mm outer dimension) and the Scenario 4 placement. These solutions were acceptable to the Roman design team. It also resulted in greatest flexibility for the future servicer since the camera FOV can range from ~5-15 deg. The recommendation was accepted by the project and is planned to be implemented.

JAMES WEBB SPACE TELESCOPE FIDUCIAL PHOTOGRAMMETRY

This section presents the measurement process, and the corresponding results, used to estimate the location of the AprilTag fiducials placed on the JWST. High resolution images (up to 11600x8700 pixels) of the JWST and its fiducials were provided allowing the implementation of a computer vision-based pose estimation system.

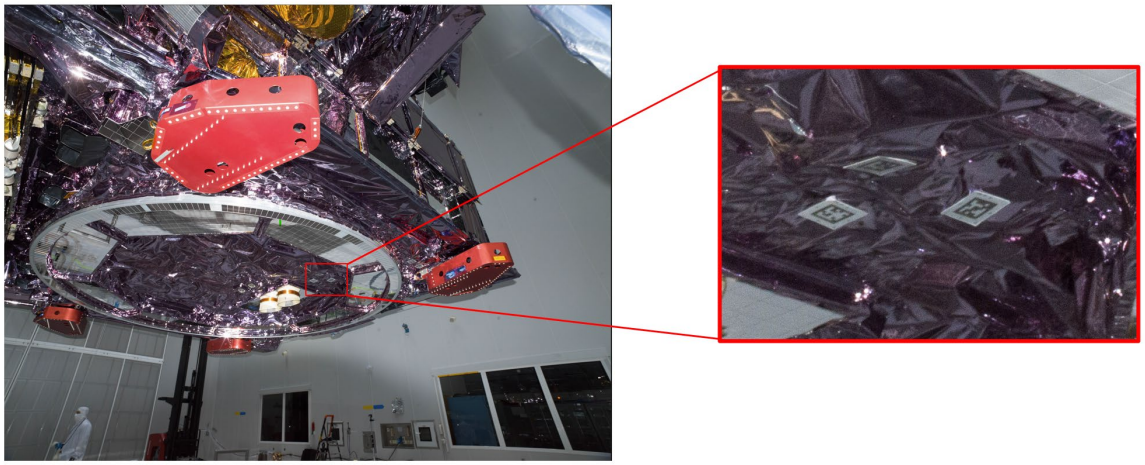


Figure 16. Fiducials on JWST in the provided high-resolution images

The pose estimation system estimates the relative pose of the fiducials with respect to the camera. In addition, a graphical user interface (see Figure 17) allows the user to select prominent natural features of the JWST in the images. The AprilTag estimated pose and the selected natural features are given to an iterative optimization process known as Levenberg-Marquardt optimization to minimize a cost function and estimate the 6DOF pose of the fiducial in the JWST local frame. The user can select several predefined natural features from several images, the only requirement is that the same fiducial is detected in each image. In addition, the coordinates of the natural features in the JWST local frame must be known, typically from a CAD model. The graphical user interface presents an image to the user, along with a magnifier window, facilitating a closer examination of the natural features and allowing their precise selection. The feature selection is performed by interactively selecting the desired points in the image using the mouse. A CAD model of the JWST is used to display the predefined natural features and to visualize the estimated pose of the fiducial. The identification numbers of the five AprilTag fiducials considered in this study are: 367, 368, 369, 370, and 371. Note, the photos provided did not include the sixth fiducial.

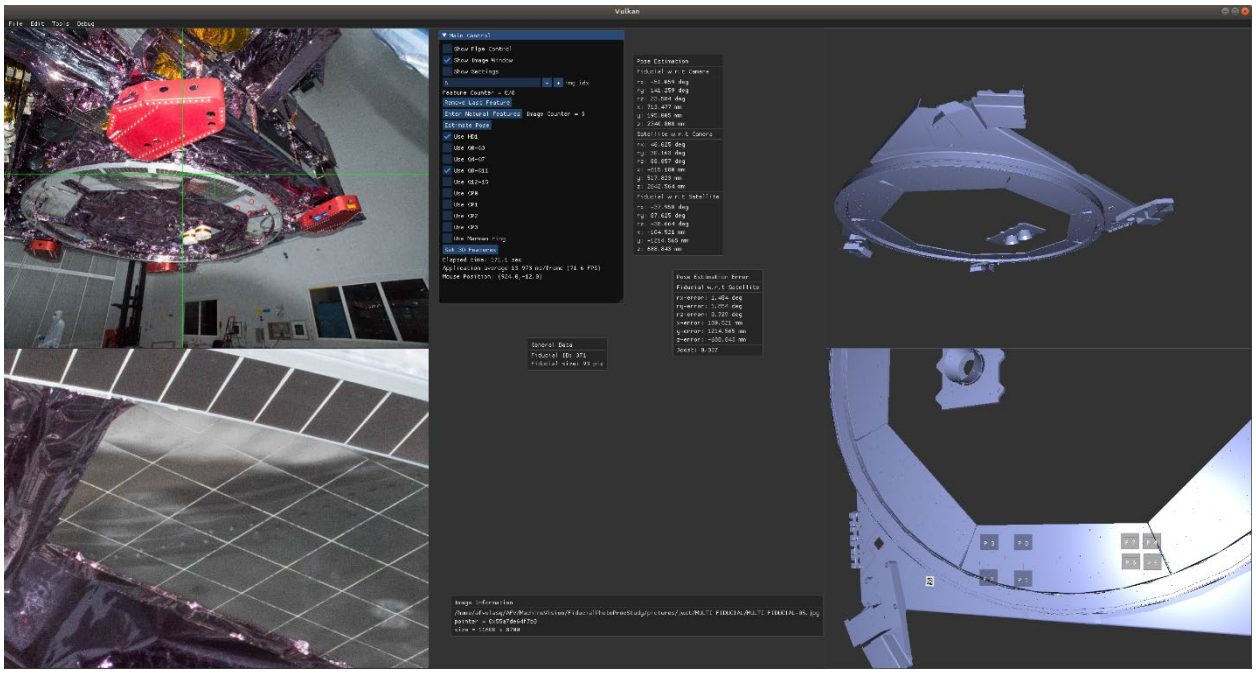


Figure 17 Graphical user interface for estimation of fiducial location

The JWST fiducials are bonded to the outer layer of the MLI on the aft deck around the launch interface adapter. Predefined nominal locations were used when placing the fiducials, but no metrology techniques were used to determine their actual location. and show the nominal locations of the five fiducials presented in this study. The nominal location does not represent the actual or as-installed location.

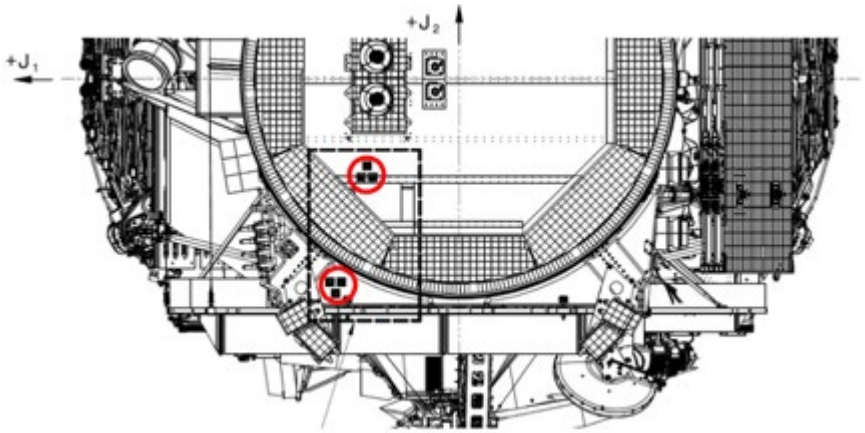


Figure 18. JWST Fiducial nominal locations

Table 2. JWST Fiducial nominal locations in the vehicle body frame

Fiducial Nominal Location			
Fiducial ID	x[mm]	y[mm]	z[mm]
367	-117.9	-523.4	555.5
368	-117.9	-592.4	590.0
369	-117.9	-592.4	521.0
370	-117.9	-1219.9	778.1
371	-117.9	-1219.9	709.0

High resolution images of JWST were taken when the vehicle was being transferred to the launch vehicle. Images late in the development flow are desired to capture the vehicle in its final configuration. The images capture the fiducials and several natural features that are suitable for pose estimation, such as the launch interface adapter, thermal tiles, and other rigid objects with rectilinear features that could be easily recognized in each image. Figure 19 shows the natural features used for pose estimation, note that the corners of thermal tiles are used for this purpose since they are solid objects with sharp corners that are easily identifiable in both the image and the CAD model of the JWST.

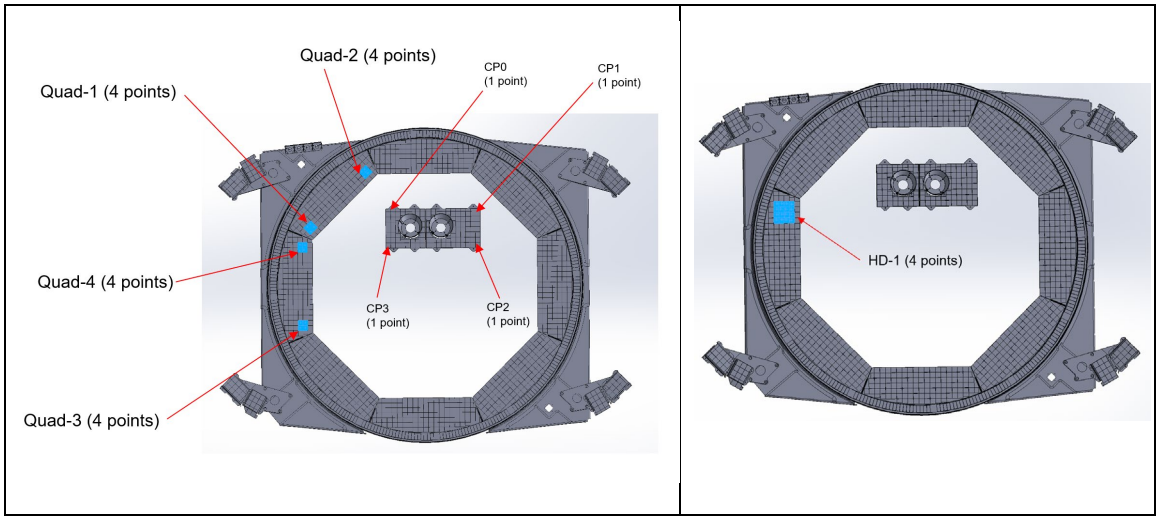
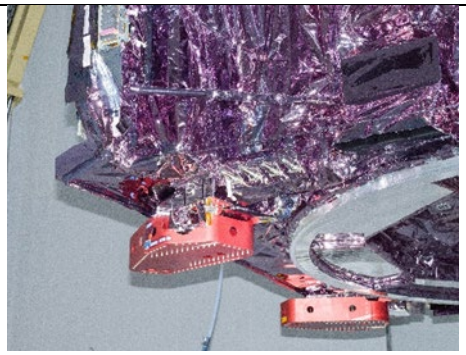
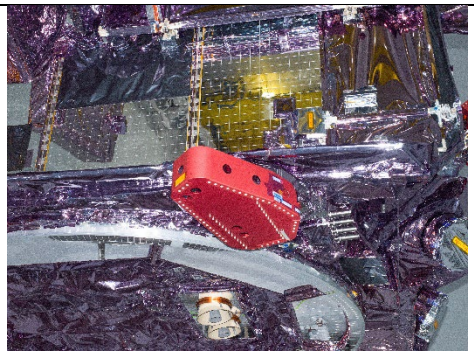


Figure 19. Natural features used for pose estimation

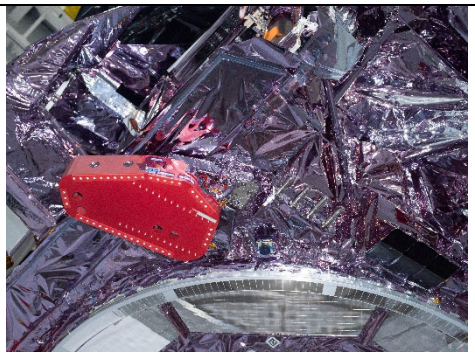
Figure 20 shows samples of the photos used in the fiducial identification.



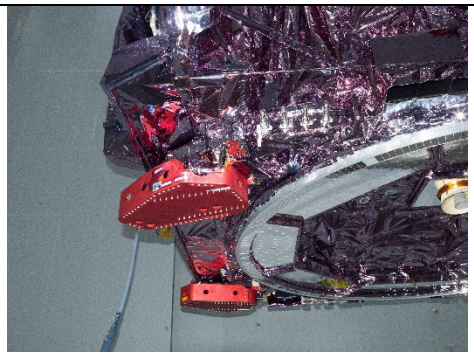
ELEVATED-24



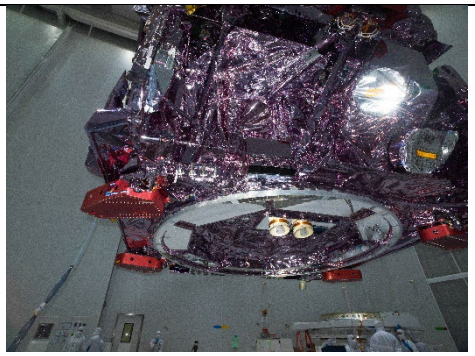
ELEVATED-29



FRONT VIEW-04



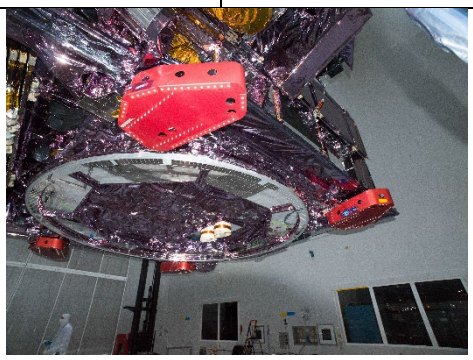
MULTI FIDUCIAL-02



MULTI FIDUCIAL-03



MULTI FIDUCIAL-04



MULTI FIDUCIAL-05

Figure 20. JWST Images

The image metadata was used to determine the intrinsic parameters of the camera necessary for the proper performance of the pose estimation system. Table 3 shows the fiducials detected in each image, along with the fiducial size in pixels, the camera focal length, and the image resolution. Table 4 shows the images and natural features used to estimate the local pose of each fiducial.

Table 3. Fiducial detection

Image	Average size of fiducial diagonal [pixels]					Detected Fiducial ID	35mm focal length	Resolution
	367	368	369	370	371			
ELEVATED-24			182			369	52mm	9345x7165
ELEVATED-29	162		166			367, 369	52mm	11600x8700
FRONT VIEW-04		221				368	33mm	11600x8700
MULTI FIDUCIAL-02	163		166			367, 369	18mm	11600x8700
MULTI FIDUCIAL-03	85		90			367, 369	18mm	11600x8700
MULTI FIDUCIAL-04	97		102			367, 369	18mm	11600x8700
MULTI FIDUCIAL-05	76	80		92	93	367, 368, 370, 371	18mm	11600x8700
Total images per fiducial:	5	2	5	1	1			

During the measurement process, each image of every test defined in Table 4 was used three times, with three independent trials conducted for each test. Each image was used three times to reduce the impact of the human error when selecting the features in the image.

Table 4. Images and features used to estimate the local pose of the fiducials.

Test ID	Fiducial	Images	Natural Features
F1	367	ELEVATED-29	Quad-1, Quad-2, CP0, CP1, CP3
		MULTI FIDUCIAL-02	Quad-1, Quad-2, CP0, CP3
F2	368	FRONT VIEW-04	Quad-1, Quad-2
F3	369	ELEVATED-24	Quad-2
		MULTI FIDUCIAL-02	Quad-1, Quad-2, CP0, CP3
F4	370	MULTI FIDUCIAL-05	Quad-3, HD-1
F5	371	MULTI FIDUCIAL-05	Quad-3, HD-1

System ID results

Figure 21 shows the average value of the 6DOF pose for each fiducial. The average is computed from the three trials performed for each test. Figure 21 also shows the range between the maximum value and the minimum value among the three trials of each test. The small difference in the solution is attributed to the manual selection of the natural features only.

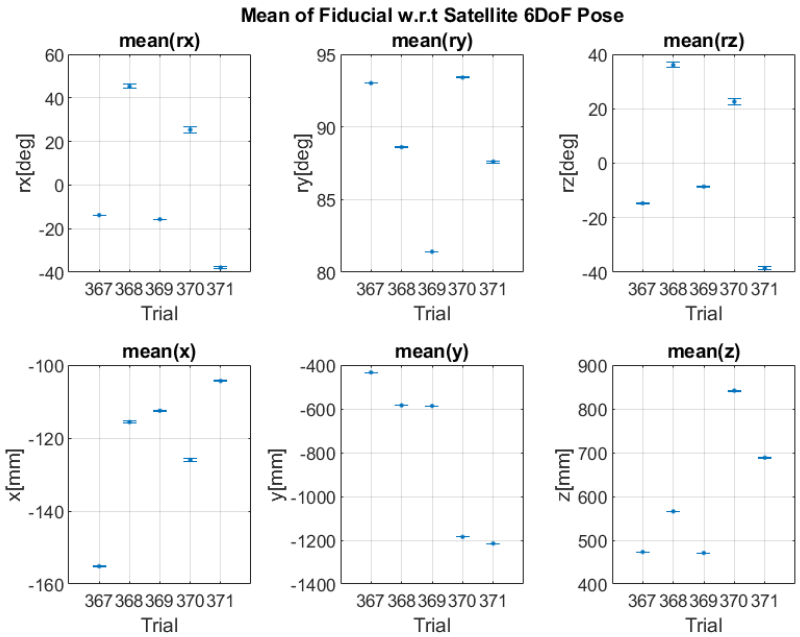


Figure 21. Mean value of the 6DOF pose for each fiducial

The dispersion of the repeatability of the test is relatively low, the worst case was 2.21mm. This dispersion occurs due to the user error when selecting the natural features, since for every test trial a slightly different pixel may be selected. In the same way, a different user will select different pixels and considerably different repeatability values may be obtained. This dispersion was reduced by using the same images multiple times. Figure 22 shows the residual of the minimized cost function for each trial of every test. The cost function represents the distance between the selected features and the reprojected features using the estimated pose, if there is a perfect estimation of the pose the cost function is zero. As can be seen, for every fiducial the residual values of the three trials are similar, meaning good repeatability. The residuals are close two zero (except for fiducials 367 and 369) which means that the optimization routine converged to a solution. The estimated positions of fiducials 367 and 369 were obtained using two images, this explains the larger residual associated to these fiducials, since matching exactly the features on two different images is more challenging if even possible.

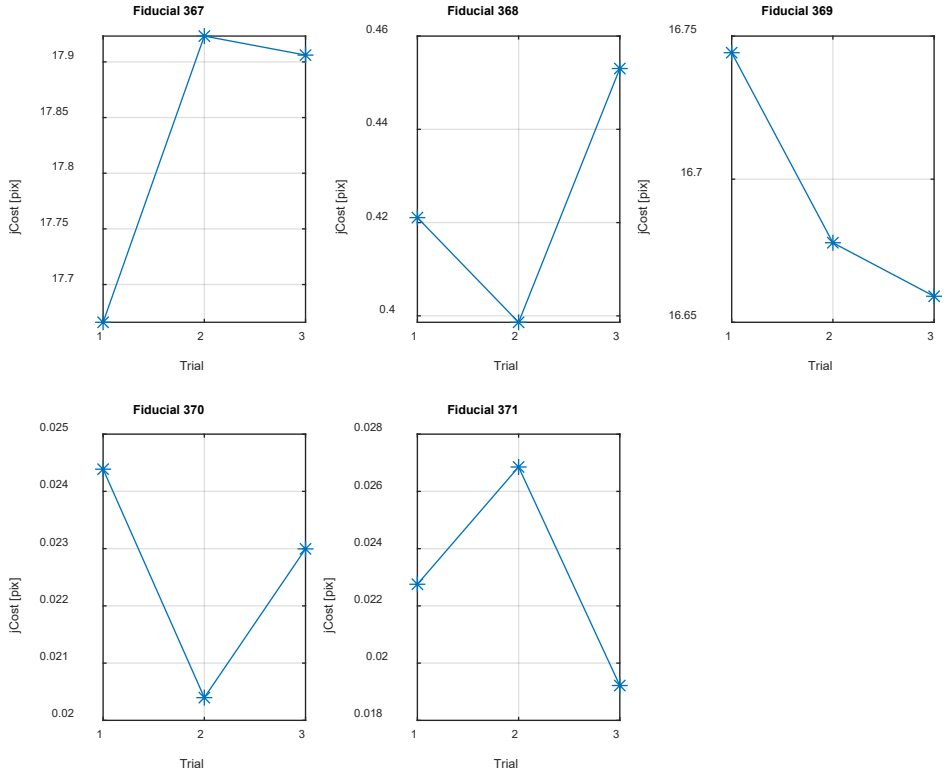


Figure 22. Cost function residuals

The fiducial orientation and associated rotation angles can be significantly different from the nominal values since they are attached to a non-rigid surface. Local wrinkles on the MLI can randomly change the fiducial orientation. The values presented in Figure 21 show that there is an important change in the fiducial orientation compared to the nominal values.

Figure 23 presents a drawing showing the difference between the nominal and estimated fiducial locations. This demonstrates the value of the as-installed system identification. A hypothetical servicer spacecraft may be challenged by the uncertainty in the fiducial locations.

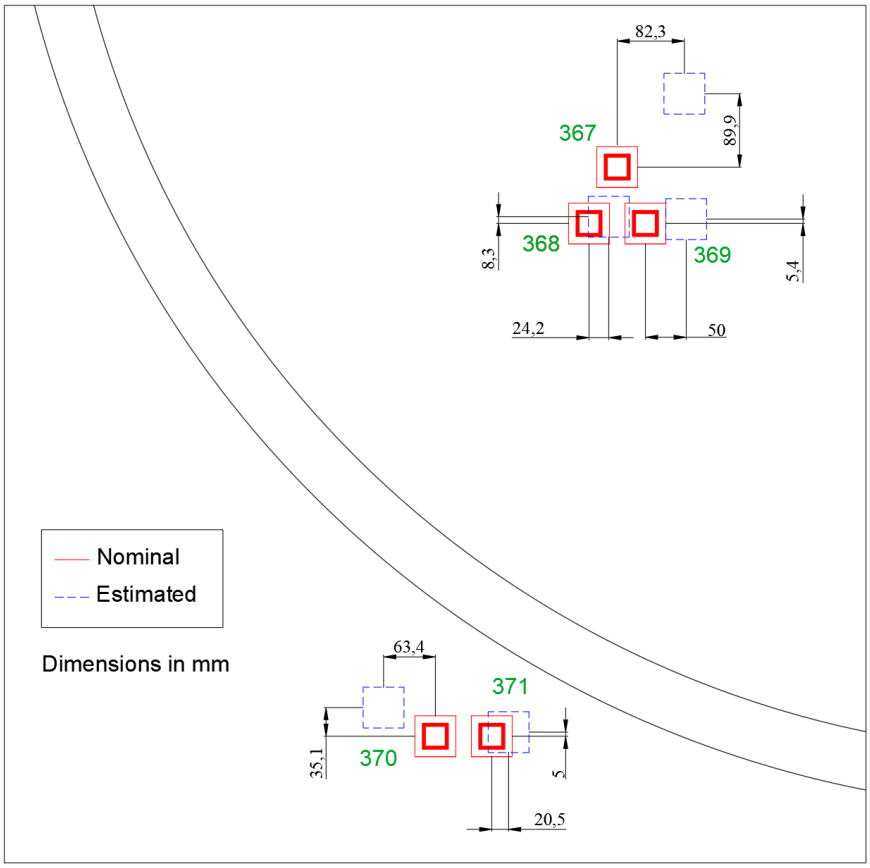


Figure 23. JWST Difference between nominal and estimated locations. Dimensions in mm

Lesson learned from JWST

The JWST photogrammetry study illustrated clearly that the instructions to the photographer were inadequate in documenting the desired fiducial information. While the high resolution was very valuable, the limited focus or resolution on the fiducials resulted in very few usable photos. Future instructions have been updated to include specific metrics about the fiducials in the images:

- Images should be captured with multiple fiducials in the same image
- The fiducials should encompass approximately 1/10 to 1/5 of the image
- At least two hard features should be included in the image i.e. thermal tiles, Marman ring, thrusters, bolt heads, metallic sharp edges/borders/corners, rectangular and circular objects
- Each fiducial should be imaged from different perspectives including incidence angle, focal length, and location of the fiducial in the image in the context of the above instructions
- Include close-up pictures of the fiducials

NASA's Exploration and In-space Services Projects Division has complete instructions for fiducial photo documentation that is available upon request.

CONCLUSION

This paper defined a process for including rendezvous fiducials into a space vehicle's design. Key aspects of the process were illustrated in detail with examples from the JWST and Roman vehicle designs. The Roman study demonstrated that the addition of fiducials can readily meet the relative state estimation accuracy requirements of the OSAM-1 rendezvous system designed for legacy client space objects. The JWST study demonstrated a method to determine the as-installed fiducial locations relative to the client space object frame through only photographs including improved actionable metrics for the photographer. The two most significant points are that (1) rendezvous fiducials are a low impact addition to a space vehicle design that can be added early or late in the design, and (2) the addition of rendezvous fiducials reduce the risk of future servicing by decreasing the complexity of the servicer spacecrafts rendezvous system design.

ACKNOWLEDGMENTS

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REFERENCES

[1] Consortium for Execution of Rendezvous and Servicing (CONFERS), "CONFERS Lexicon", March 2023, https://satelliteconfers.org/wp-content/uploads/2023/06/CONFERS_Lexicon_Paper-20233103.pdf.

[2] Executive Office of President of the United States, "In-Space Servicing, Assembly, and Manufacturing National Strategy," Product of ISAM Interagency Working Group of the National Science & Technology Council, April 2022.

[3] "Cooperative Servicing Aids," NASA GSFC, December 2012, https://nexis.gsfc.nasa.gov/cooperative_servicing_aids.html

[4] H. Kato and M. Billinghurst, "Marker tracking and hmd calibration for a video-based augmented reality conferencing system," in Augmented Reality, 1999. (IWAR'99) Proceedings. 2nd IEEE and ACM International Workshop on. IEEE, 1999, pp. 85–94.

[5] D. Wagner, G. Reitmayr, A. Mullein, T. Drummond, and D. Schmalstieg, "Pose tracking from natural features on mobile phones," in ISMAR '08: Proceedings of the 7th IEEE/ACM International Symposium on Mixed and Augmented Reality. Washington, DC, USA: IEEE Computer Society, 2008, pp. 125–134.

[6] M. Fiala, "ARTag, a fiducial marker system using digital techniques," in Computer Vision and Pattern Recognition, 2005. CVPR 2005. IEEE Computer Society Conference on, vol. 2. IEEE, 2005, pp. 590–596.

[7]E. Olson, "AprilTag: A robust and flexible visual fiducial system," in Proceedings of the IEEE International Conference on Robotics and Automation (ICRA). IEEE, May 2011, pp. 3400–3407.

[8] E. Olson, "AprilTag 2: Efficient and robust fiducial detection," in Proceedings of the IEEE International Conference on Intelligent Robots and Systems (IROS), October 2016.

[9] Z. Tomlinson, W. Gallagher, J. Cassidy, B. Roberts, K. Facciol and J. Easley, "Lessons for Future In-Space Telerobotic Servicing from Robotic Refueling Mission," 2022 IEEE Aerospace Conference (AERO), Big Sky, MT, USA, 2022.