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PGHM Vision Measurement System

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For installation of payloads into the Orbiter cargo bay while at the pad, the payload is delivered to the launchpad in a canister. The payload is then transferred into the payload bay of the Shuttle Orbiter. The mechanism responsible for manipulating the payload, the Payload Ground Handling Mechanism (PGHM), consists of a set of movable J-Hooks that lift the payload by its trunnions. Successful, safe integration of the payload requires careful position measurement of the J-Hooks relative to the payload trunnions and the payload relative to the Orbiter payload bay. Due to the complex nature and high mission-to-mission variability of the geometry involved with the flight hardware, rulers are presently the best way to measure these relative positions; however measurement with rulers is difficult, time-consuming, and relatively inaccurate. The PGHM Vision Measurement System alleviates this measurement problem by using a standard inexpensive, RS-170, monochrome camera coupled with digital image processing to precisely measure the relative position of the payload. The image processing algorithms are specifically designed to locate and track uniquely designed targets. The system accurately measures the X, Y, and Z position of the payload via the vector position of the targets. The vision measurement system is currently being integrated into the PGHM.

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PGHM Vision Measurement System

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Abstract

For installation of payloads into the Orbiter cargo bay while at the launch pad, the payload is delivered to the pad in a canister. The payload is then transferred into the payload bay of the Shuttle Orbiter. The mechanism responsible for manipulating the payload, the Payload Ground Handling Mechanism (PGHM), consists of a set of movable J-hooks that lift the payload by its trunnions. Successful, safe integration of the payload requires careful position measurement of the J-hooks relative to the payload trunnions and the payload relative to the Orbiter payload bay. Due to the complex nature and high mission-to-mission variability of the geometry involved with the flight hardware, rulers are presently the best way to measure these relative positions; however, measurement with rulers is difficult, time-consuming, and relatively inaccurate. The PGHM Vision Measurement System alleviates these measurement problems by using a standard, inexpensive RS-170 monochrome camera coupled with digital image processing to precisely measure the relative position of the payload. The image processing algorithms are specifically designed to locate and track uniquely designed targets. The system accurately measures the x , y , and z position of the payload via the vector position of the targets. The vision measurement system is currently being integrated into the PGHM.

Payload Installation Procedure

Preparing a Space Shuttle for launch involves numerous steps requiring many months to complete. The Orbiter vehicle itself is processed in the Orbiter Processing Facility (OPF). The Orbiter is then moved to the Vehicle Assembly Building (VAB) where it is mated in a vertical position with the External Tank and the Solid Rocket Boosters (SRBs). After vehicle assembly on the Mobile Launcher Platform, the crawler transporter moves the entire assembly to the launch pad. There are also numerous processing steps that take place at the launch pad.

Of course, one of the primary goals of the Space Transportation System (STS) is to ferry payloads into low Earth orbit. In processing the Space Shuttle, one of the most important procedures is installation of the payloads into the payload bay of the Orbiter. See Figure 1 for a picture of the Orbiter and location of the payload bay. Payload installation typically takes place either in the OPF, where the Orbiter is in the horizontal position, or at the launch pad, where the Orbiter is in the vertical position.

The most common installation of payloads is at the launch pad shortly before launch. For vertical installation, the payloads are prepared at a separate facility in a payload canister. This canister serves to protect the payload during transportation to the launch pad. After the assembled Space Shuttle is moved to the launch pad, the payload canister is then transported to the launch pad.

At the launch pad, the Rotating Service Structure (RSS) is retracted away from the vehicle. The payload canister is then mated with the Payload Changeout Room (PCR). This room is an environmentally controlled clean-room-type enclosure. It has a set of outer airlock doors with inflatable environmental seals¹ so that the payload may be transferred from the payload canister into the PCR without exposure to the external environment. After the payload is transferred into the PCR, the airlock doors are closed and the empty payload canister is removed from the RSS. The RSS is then rotated to mate with the Orbiter payload bay. (See Figure 2 for a picture of a payload mid-transfer in the PCR). The Orbiter payload bay doors and the PCR doors are

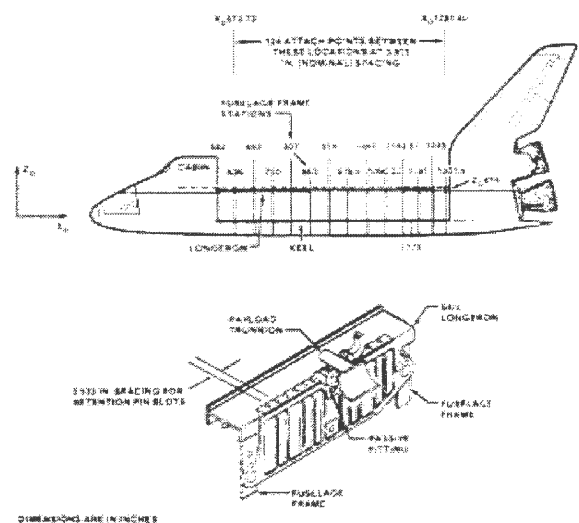


Figure 1. Space Shuttle Orbiter and Payload Retention System.



Figure 2. S-1 truss mid-transfer for STS-112.

opened. The payload is then transferred from the PCR into the Orbiter payload bay. The Orbiter and PCR payload bay doors may then be closed, completing the transfer into the Orbiter.

Payload Retention System

Payloads to be installed in the payload bay of the Orbiter are fitted with trunnions. Payload trunnions are metallic rods approximately 3 inches in diameter and are meant to fit to latches on the sills of the payload canister and the Orbiter payload bay. (See Figure 1.) Typically, there are sill trunnions on either side of the payload and a keel trunnion in the center to be mated with the keel latch in the bottom of the payload bay.

The payload canister and the Orbiter payload bay contain latches that are designed to retain the payload trunnions. There are two general categories of latches: passive and active. Passive latches are manually actuated and only actuated on the ground. The canister latches are passive and there is only a single type. Orbiter latches may be passive or active, and there is only a single type of passive Orbiter latch. There are several types of active Orbiter latches, including standard, lightweight, middleweight, and supermiddleweight. Active latches are motorized for remote actuation control and may be operated on-orbit.

Payload Ground Handling Mechanism

Payloads can be up to 15 ft in diameter and 55 ft long and can weight up to 65,000 lb.² Manipulation of payloads is a complicated process due to their size, weight, complexity, flexibility, and environmental sensitivity. In the PCR, the mechanism that moves the payload from the payload canister, into the PCR, and into the Orbiter payload bay is called the Payload Ground Handling Mechanism (PGHM). This system consists of a 5-story-tall platform that rolls in the Orbiter z direction (see Figure 1).

After gross translation of the PGHM, each trunnion is carried by an individually actuated J-hook. The J-hooks appear much like horizontal fingers with 3-inch-diameter, semicircular slots to capture and hold the payload trunnions from the bottom of the trunnion. Figure 3 shows a typical J-hook.

Current Measurement Method

There are many different methods of distance measurement: theodolites, laser trackers, linear variable differential transformers (LVDTs), etc. However, due to the complex nature of the flight hardware involved and the need for measurements in real time, the only measurement method that currently is reliable and versatile enough while remaining cost-effective is manual measurement. For payload transfer, a J-hook operator is located at each payload J-hook/trunnion/latch position on the PGHM. The J-hook operator uses a tethered scale to measure the distance between the trunnion centers, with a resolution of 0.1 inch (see Figure 4). The PGHM is moved slowly as each J-hook operator calls the measurements back



Figure 3. J-hook operator observes transfer during STS-83. The J-hook is in the center of the image.



Figure 4. J-Hook operator measuring distance from trunnion to a closed passive latch with a tethered scale. Note the fall protection on the J-Hook operator.

to the move director. In addition to measurement with the scale, the J-hook operator observes all portions of the payload in the vicinity and can halt the transfer at any time to avoid an obstruction or eminent payload collision.

Typically, the move director will call for a finite-length movement and wait until the movement is complete. The move director will then ask for measurements from the J-hook operators. The move director gathers the information communicated from each J-hook operator and formulates an overall picture of the payload transfer. The move director assesses the individual J-hook positions and then determines how the PGHM and/or the individual J-hooks are to be subsequently actuated.

Motivation To Improve the Payload Transfer Process

There is a J-hook operator at each trunnion position. There can be up to 20 trunnion positions for a single payload transfer. Each measurement requires the J-hook operator to lean out over the payload, in some cases up to 5 stories over the PCR floor. There are on the order of a hundred measurements taken of each trunnion position during each transfer. The number and circumstances of the measurements required put the J-hook operator in considerable risk of falling (fall protection gear can be seen in Figure 4), pinching, crushing, slipping, etc. In addition, the payload is under some risk of damage if something were dropped from height.

The move director has a large amount of information that must be assimilated from the J-hook operators. Each measurement must be verbally communicated by the individual J-hook operator. This can be extremely time-consuming. A payload transfer from the canister into the Orbiter payload bay can require two 8-hour shifts to complete.

The issues and risks associated with the payload transfer process were studied to see if the process could be improved for both safety and performance. Of all the technologies able to solve the problem, the most cost-effective, flexible system was determined to be a machine vision system.

Machine Vision Measurement System Theory

A machine vision system consists of a camera to acquire images and a computer to process the images. There is a one-to-one correspondence between the two-dimensional (2-D) images acquired by the camera and the three-dimensional (3-D) world. To translate the pixel value of a point in the 2-D image to the corresponding 3-D coordinate of the point, some information must be known about the image.

For the purposes of this paper, if it can be assumed that:

1. the target is flat and its plane is exactly perpendicular to the camera's optical axis (a line in the center of the image, perpendicular to the image extending to infinity),
2. there are two points in the image whose distance is known,
3. the pixels of the camera are square, and
4. there is no lens distortion of the image,

then some simple relations are valid to translate from pixel coordinates to the coordinates of a point in 3-D space relative to the optical axis of the camera. Given two known points on the object, (x_1, y_1) and $(x_2,$

y_2), and their corresponding points in the image, (m_1, n_1) and (m_2, n_2) , then a scaling factor S can be defined as:

$$S = \frac{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}}{\sqrt{(m_1 - m_2)^2 + (n_1 - n_2)^2}} \quad (1)$$

In addition, a parameter α can be defined as:

$$\alpha = \frac{f}{d_c} \quad (2)$$

where f is the focal length of the camera lens, and d_c is the camera pixel size. With these relations defined, the 3-D coordinates of any given point in the image are simply:

$$\begin{aligned} x &= S(m - m_c) \\ y &= S(n - n_c) \\ z &= \alpha S \end{aligned} \quad (3)$$

where the coordinates of the point in the image are (m, n) , the center of the image is (m_c, n_c) , and the 3-D coordinates of the point in space relative to the optical axis of the camera, with z being coincident with the optical axis, are (x, y, z) . $z=0$ defines the CCD plane of the camera and $x=y=0$ defines the optical axis.

The authors have worked out the general cases without the assumptions listed above, the associated error estimates, estimates of resolution, etc., but for brevity, these will not be presented here. For the assumptions given, these equations are remarkably simple and provide quite accurate results.

Target Recognition Strategy

As stated in the previous section, some real-world information must be known about the images to solve equations (1) through (3). One simple method of acquiring information about the image is to place targets (whose size and position information is known) in the field of view of the camera. The authors have developed a target along with a specially designed image processing convolution filter that allows the target to be uniquely located in the image. The details of the mathematics will not be presented in the paper, but Figure 5 shows the results of processing an image with the specially designed target and filter.

The target/convolution filter design as shown in Figure 5 lends itself directly to equations (1) through (3) because the scaling factor S can be directly measured from the known point spacing of the target points shown in the last frame of Figure 5. In addition, the position of the target can be defined as the center of the eight points shown in Figure 5. The target/convolution filter design has proven to be extremely robust and has been tested in a myriad of different lighting conditions, backgrounds, and environmental conditions.



Figure 5. Images showing the novel target/convolution algorithm. The left frame shows the raw image from the camera, including the target. The center frame is the image after applying the convolution filter. The right frame is after thresholding. Notice how the target is uniquely located.

Experimental Verification of Vision Measurement System

The first step in experimentally proving that the Vision Measurement System could be applied to payload position measurement was to place a target on a high-accuracy x - y table. The table was automatically positioned over the same range where measurements are necessary, and the Vision Measurement System was coordinated to acquire data while the x - y table scanned over the region of interest. The x - y table was used to investigate various camera-lens combinations, the accuracy of the system, the effects of lens distortion, the interchangeability of same-model lens-camera combinations, and many other factors. An example of the resulting data of one of the best camera-lens combinations is shown in Figure 6. The plots shown are error plots. Each plot shows the difference between the measurements of the Vision Measurement System and those reported from the x - y table. Areas in green are where the error is less than 0.025 inch.

To use the Vision Measurement System for installing payloads, there were, of course, numerous requirements. The measurements must be accurate to 0.05 inch in x , y , and z at mating. At mating the camera-target separation is on the order of 12 inches. Figure 6 clearly shows that the Watec 902c/Tamron 8-mm lens meets the accuracy requirement. It was also required that the field of view be approximately 3 inches at seating. The Watec/Tamron lens selection also meets the field-of-view requirement.

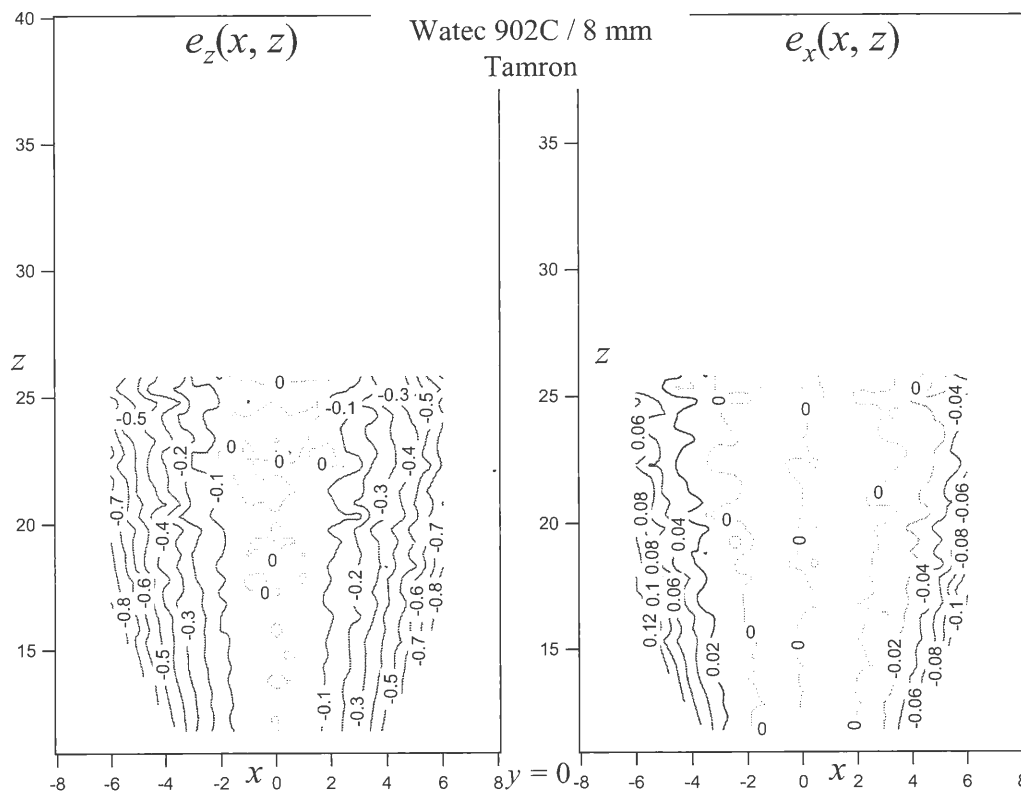


Figure 6. Error plots for Watec 902c camera with Tamron 8-mm lens. All units are in inches. e_z is the error of the Vision Measurement System in the z direction; e_x is the error in the x direction. The data are plotted relative to the optical axis of the camera. Green indicates the error is less than 0.025 inch. Other colors indicate error greater than 0.025 inch.

Another method used to verify the system performance involved applying the algorithm to a larger-scale system. For this experiment, 1-inch targets were printed and placed in a large high bay. A surveying crew measured the exact position of the targets. The surveying results were then compared with the measurements taken by the Vision Measurement System. The experiment resulted in good

agreement between the results obtained by the surveying crew and the Vision Measurement System. Figure 7 shows an example of the Camera Measurement System applied to a surveying scale application.



Figure 7. Camera Measurement System used in a surveying scale application.

PGHM Camera Measurement System

After experimental work in the lab, the system was implemented in the field. Limited prototype versions of the system were installed for payload transfers of STS-108, STS-110, and STS-113. For archival purposes, the progress of the payload transfer for these three launches was recorded on DVD.

The Vision Measurement System as applied to the PGHM is known as the Camera Measurement System. It consists of an inexpensive off-the-shelf RS-170 camera, a specially designed target (as shown in previous sections), LED illumination, a standard desktop computer with an image capture card, and custom-developed image processing software. The system measures the 3-D vector coordinates from the camera's optical axis to the target. An early hardware prototype that was deployed and evaluated during the STS-113 payload installation is shown in Figure 8.

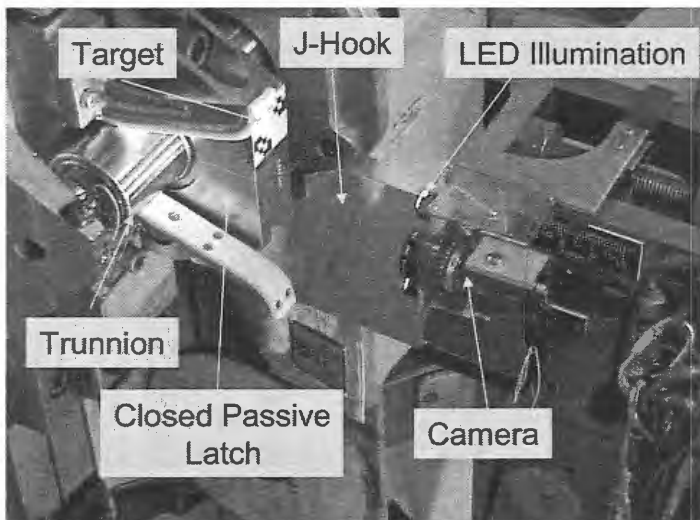


Figure 8. Early prototype PGHM Camera Measurement System deployed for STS-113.

The bracket holding the camera assembly attaches at points on the Z-bar/J-hook using preexisting tapped holes. The anchor points selected allow the entire camera bracket assembly to translate with the J-hook in all possible actuation degrees of freedom. This is an important point to note since the design forces the distance and orientation between camera and J-hook to be fixed.

LED illumination provides a semiconstant light level for the camera imaging of the target. The target is fixed in a carefully chosen position on both the canister and Orbiter payload bay latch. Since the camera translates with the J-hook and the target is fixed on the latch, the Camera Measurement System can be used to

get the vector from the J-hook to the latch.

The vector addition is shown in Figure 9. During preoperation setup, when the bracket is being installed on the J-hook, a fixture with a Camera Measurement System target is placed in the J-hook saddle. With this fixture in place, vector 1 is measured and stored. The target is located at a prechosen position so that vector 3 is known. The Camera Measurement System measures vector 2 in real time at approximately 30 samples per second, the limit of acquisition of the RS-170 camera. The resultant vector **R** is calculated in real time by adding vectors 1, 2, and 3.

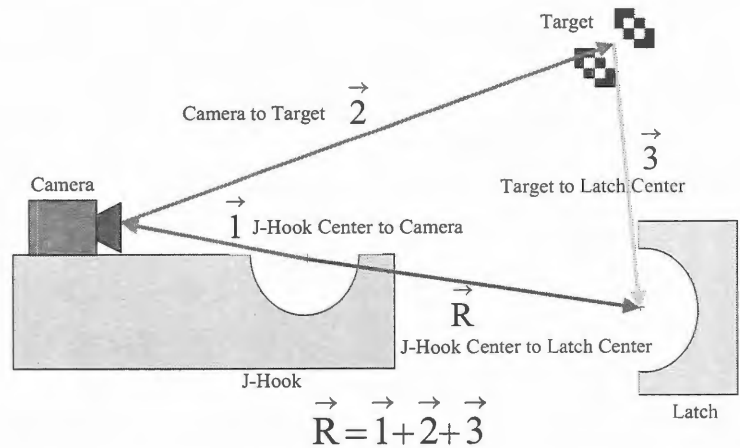


Figure 9. Camera Measurement System measurement vectors: vector 1 is measured during setup; vector 3 is known; vector 2 is measured in real time; and vector R, the vector of interest, is calculated in real time.

Conclusions and Future Work

The Camera Measurement System is an excellent method for measuring the 3-D position of points in space. Experimental verification both in the laboratory and in the field shows that the system can be successfully integrated into the PGHM and provide accurate robust measurements of position during payload transfers. The system is currently being integrated into a final operational system.

The targeting strategy developed to solve the PGHM position measurement problem has led to an extremely robust and quite general method for automated location of targets in the field of view of a camera. The convolution filter – target – machine vision software may be easily applied to other position measurement problems. The algorithm easily scales to different orders of magnitude as demonstrated by the surveying application. The technology developed for the Camera Measurement System could be applied to numerous other position measurements that are needed during Shuttle processing, as well as to other commercial applications, such as surveying and construction.

The system presently uses targets that are attached to the latches in both the canister and the Orbiter. The Camera Measurement System will record images from each of the cameras, and most likely within a few payload transfers, unique “landmarks” in the images can be identified. Robust automated location of features will obviate the need for targets. The advantage of a machine vision-based system is that the software used to process the images is easily upgradeable. At a later date, with a simple software update, it may be possible to eliminate attached targets altogether.

References

¹<http://www-pao.ksc.nasa.gov/kscpao/nasafact/count4rss.htm>

²<http://shuttlepayloads.jsc.nasa.gov/flying/accommodations/payloadbay.htm>

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