Development of an Electromechanical Ground Support System for NASA's Payload Transfer Operations: A Case Study of Multidisciplinary Work in the Space Shuttle Program

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ABSTRACT

Space shuttle Atlantis was launched from Kennedy Space Center on July 8, 2011 and landed on July 21, 2011, the final flight of the 30-year Shuttle Program. The development and support of the Space Transportation System (STS) had required intensive coordination by scientists and engineers from multiple program disciplines. This paper presents a case study of a typical multidisciplinary effort that was proposed in the late 1990's. The proposed conceptual development of a portable Electronic Ground Support System (EGSS) for transporting payloads before their integration with space launch vehicles was not adopted since its accuracy requirements were not met within the desired schedule. However, the proposed EGSS was appealing since the conventional system used for NASA's payload transfer operations drew upon many resources and required manual calculations, which made the operation time-consuming and hazardous. For these reasons, a self-calibrating, simple, robust, network-operated, portable electromechanical system was developed to automatically measure and display coordinate offsets between spacecraft payload trunnions and their supports during payload transfers. These payload operations occurred in the payload canister room at the launch pad, and in other payload processing facilities.

Keywords: space shuttle, electromechanical ground support system, multidisciplinary work.

1. INTRODUCTION

This paper shows how a data acquisition and control system may be used to improve the payload transfer process by integrating a fast calculation of the next move command and closed-loop control of the operation. The implementation of the proposed electromechanical system will minimize the risk and decrease the cost of these hazardous payload transfer operations in current and future space programs.

1.1 Space Shuttle Program

The National Aeronautics and Space Administration (NASA) initiated experimental space missions in 1958; and, on May 5, 1961, astronaut Alan Shepard flew on the first space manned mission under Project Mercury. Since then, there have been many manned missions under Project Gemini, the Apollo Program, the Skylab Program, and the Apollo-Soyuz Program, which had it last flight in July 1975. Next came the Space Shuttle Program, NASA's longest space program, with 30 years of manned missions, from 1981 to 2011. A fleet of five crewed vehicles (orbiters) supported 135 Space Transportation System (STS) flights. During the first 15 years of the program, the mission objectives were mostly dedicated to launching and refurbishing satellites and life sciences studies in free-fall or microgravity. Meanwhile, flight hardware was being developed and tested before being sent to space for the construction of the International Space Station (ISS).

The STS was capable of rocketing as many as eight astronauts and 60,000 pounds of payload to low-Earth orbit (LEO) and returning them to Earth, with the orbiter landing like a glider as shown in Figure 1.

Figure 1. STS liftoff to landing sequence

Once the spacecraft was committed to land on Earth, it would land at the Kennedy Space Center (KSC) in Florida (the desired landing location because it shaved about 5 days off the time needed to process the shuttle for its next mission), at the Edwards Air Force Base in California, or at the White Sands Test Facility in New Mexico. If the orbiter landed in California or in New Mexico, then it was mated to the top of a Boeing 747 and returned (ferried) to Florida.

1.2 Space Shuttle System Overview

The Space Transportation System (STS) had three main components: (1) the orbiter "crewed vehicle," (2) the external tank, and (3) the solid rocket boosters (SRBs). The orbiter and the SRBs were reused; but the external tank was expendable and burned in the atmosphere during reentry. These components were integrated at KSC's Vehicle Assembly Building before the shuttle vehicle was transported to the launch platform for final payload installation and launch countdown activities. The three main STS components had their own subsystems that had to function harmoniously for a successful mission. Every subsystem component was tested on the ground and qualified for spaceflight.

The orbiter carried the crew and payloads into space. It contained the guidance and navigation subsystems, as well as the communications and tracking systems that provided voice, video, and data transmission for the onboard astronauts, spacewalking astronauts, and the ground crew team. The external tank provides the fuel (liquid hydrogen) and oxidizer (liquid oxygen) required by the orbiter's three main engines during liftoff. After separation from the orbiter, the external tank disintegrated as it came down through the atmosphere. The two long white rockets attached along the side of the external tank were the SRBs. The fuel in the SRB motors was a mixture of ammonium perchlorate (oxidizer), aluminum (fuel), iron oxide (catalyst), a polymer (PBAN or HTPB) and an epoxy curing agent [1]. They were reusable and were retrieved from the ocean after each flight, as shown in Figure 1.

The STS was a multidisciplinary system with interdependent functions. These systems required the integration of Flight Support Equipment (FSE) and Ground Support Equipment (GSE). In addition, electrical GSE subsystems often were integrated with mechanical, fluids, and avionics subsystems. During the countdown to launch, the workers in the Launch Control Center (LCC) at KSC would collaborate with those in other NASA Centers, such as the Johnson Space Center in Houston, the Marshall Space Flight Center in Huntsville and the Wallops Flight Facility in Wallops Island, with each discipline providing status information on the readiness on the many subsystems supporting the launch. For the purposes of this paper, the emphasis will be on the ground processing resources used during payload transfer operations rather than ground and flight support systems.

The required resources must work interpedently of each other to ensure mission success. This implies that multi-disciplined experts have to be open-minded and aware of the effect that their subsystem may have on the bigger picture. Sometimes the greatest challenge is not of a technical but human in nature. Achieving agreement among system experts could be a long and tedious process if they are hoping to optimize their design without regarding the effect on other stakeholders. A change to a requirement or the project/program scope, or a structural change, can have major consequences on a program's cost, schedule, and technical performance.

2. BENEFITS OF INTEGRATING MULTIDISCIPLINES

Some of the functional responsibilities of the resources that were involved in the development of this multidisciplinary design included:

a) Electrical Engineers who supported the signal processing, control systems design, and testing of electromechanical system.
b) Mechanical Engineers who supported the analysis, structural design of the device, and testing of electromechanical system.
c) Computer Scientists who supported the programming and development of the user interface.
d) Machinists who supported the fabrication of the mechanical design.
e) Electronic Technicians who supported the assembly, installation and troubleshooting of the electrical interfaces.
f) Mechanical Technicians who supported the assembly of the mechanical design.
g) Logistics Engineers who supported the parts selection and acquisition.

One of the preferred methods to make better use of the limited resources was to incorporate automation in tasks that were tedious and repetitive such as a payload transfer operations. To achieve the desired results it was essential that signal processes, physical models, prognostics, adaptive systems and the integration of many other disciplines occurred. Additionally, automating data calculations and providing a real-time system that could efficiently and safely perform this task would prove to be extremely beneficial.

2.1 Automating Data Acquisition Systems

In many cases, a system engineer will find that there can be substantial cost reduction if an operation or process can be automated. In order to achieve successful space missions, many ground processing activities occur at KSC before, during, and after the vehicles' flight to space. This paper addresses the automation of some of the ground processing activities (such as the former space shuttle payload transfer operation to reduce cost. KSC has been one of the premier sites in the world for the processing of space launch vehicles. The automation of the one component of these ground processing activities can create substantial cost savings (over 28%) as essential employees would be needed for a shorter time to support this task, thus allowing them to perform more activities in any given day [2].

The time needed to mate a payload to its launch vehicle (or the orbiter cargo bay, in the case of the space shuttle) is one of the main factors contributing to the operational cost. Operational costs reduction has been one of the economic challenges faced by the aerospace industry [3]. For this reason, an automated approach for use during payload transfer was developed. Specifically, each technician's trunnion station is automated. An electromechanical sensor detected the displacement of the respective trunnion and processes the information dynamically [4]. Each of the electromechanical devices measured about 128 cubic inches (4" wide, 4" long, and 8" high) or 325.12 cubic centimeters. Each sensor was networked and its respective measurements are fed back to a portable computer. The computer's graphical user interface (GUI) displayed the distances that the payload trunnion technicians were previously collecting manually. At this time, these measurements were accurate within a twentieth of an inch (0.127 cm).

2.2 Concept of Operations

Using the automated system, the payload coordinator can rely on a real-time system that is very accurate. In addition, the system shows the physical orientation of the payload with respect to its final mating position. The portable computer system can process each measurement and devise the next move based on the position of the payload. This system offers advantages with respect to cost, accuracy, speed, convenience, and safety because it has the following features:

- Automatic data acquisition
- Accurate readings by payload technicians
- Less time needed for calculation of next move
- Pictorial overview of payload position

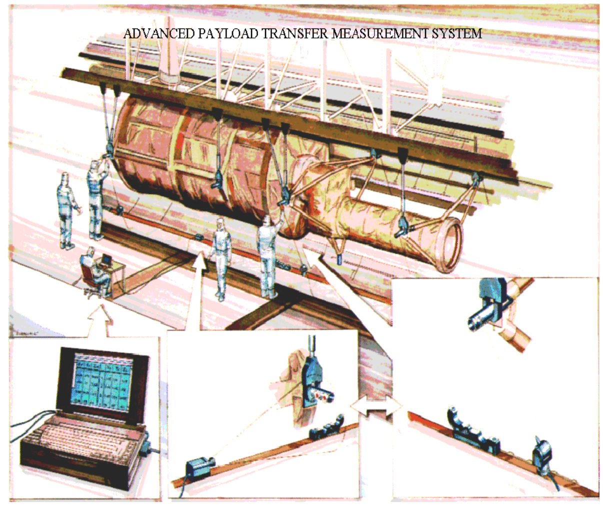

Figure 2. Payload Transfer Measurement Concept

A typical scenario is represented in Figure 2. The payload coordinator monitors the operation through the portable computer's GUI while validating its information whenever necessary. The networked electromechanical units are located near each of the trunnions, but at a safe location. These sensors are easily mounted and activated for immediate data acquisition. Each facility has different mounting locations, and some of the mounting areas at the various facilities are different. Some payload installations have a secondary (moving) trunnion, which is positioned after the primary "fixed" trunnions are locked in.

The mounting versatility of the proposed system was considered because its operating range depends on the location of installation. The mounting location of the automated system may introduce new sources of error caused by the weight and angle of the payload's envelope during displacement detection.

This automated system achieved considerable cost reduction in at least one of the fixed and variable cost areas. It improved accuracy, contains a more convenient man-machine interface, and enhances the operation's safety. Each payload transfer technician could stand in a location nearby but away from a hazardous area.

The autonomous design presented could be upgraded to include a portable wireless system to expand its flexibility around the perimeter of the payload. This would have allow a wireless interconnect between the portable computer communication's port (RS-232 via RS-485) and the Network Interface Units. This system could have been modified to be mountable in various elevations and on conducting structures by using an attachable magnet. Multidimensional measurement apparatuses are available commercially [5]. However, they were expensive and hard to maintain, were not networked, and were larger than the automated design given here, which was portable, reliable, and efficient.

3. PROPOSED SYSTEM CONFIGURATION

The proposed portable data acquisition system, called the Advanced Payload Transfer Measurement System, was developed to measure three-dimensional offsets between objects a few feet apart. It was developed specifically for measuring offsets between spacecraft payload trunnions and trunnion supports during ground-based payload-transfer operations. A trunnion is a physical supporting beam that holds the payload against the payload’s cargo bay. There could be more than a dozen of these trunnions around a large payload. A payload technician is assigned to monitor each of these trunnions.

The proposed system could also be readily used to measure offsets to guide the maneuvering of large objects during the assembly of heavy machinery or structures. The signal processing system eliminates the need for time-consuming, tedious, error-prone measurements obtained by using such tools as scales, tapes, and protractors, followed by equally tedious and error-prone manual calculations, recording of data, and verbal communication.

The raw measurement data produced from system signals are transferred into a spherical coordinate system. This real-time acquisition system includes a mechanical unit, part of which rotates about a nominally vertical and a nominally horizontal coordinate axis, as shown in Figure 3. The coordinate axes are defined by mating of the nominally stationary base of the mechanical unit with a mounting bracket on the first of the two objects. Measurements will be taken of the offsets between these objects. The mechanical unit contains a spring-loaded reel, on which is wound a 0.25 in (6.35 mm) timing belt. Two optical encoders (digital sensors) measure the rotations of their code wheel about the vertical and horizontal coordinate axes (azimuth and elevation angles, respectively). A third optical encoder measures the rotation of the reel for determining the length of timing belt pulled out. It measures the radial displacement of the axial origin to the tip of the outstretched belt. The spring-activated reeling drum allows the extended timing belt to return to its initial position outside the “nose” of the timing belt pulley when not in use. At this location, the system coordinates are at their initial state.

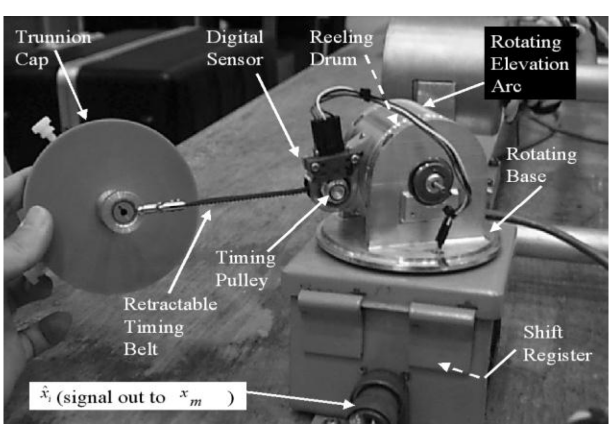

Figure 3. Electromechanical Unit Extended with Trunnion Cap

To take a measurement, a payload technician simply resets or “zeros in” the electromechanical unit by pressing a reset button. Then, the technician proceeds to connect the end of the trunnion cap to the “dummy” trunnion and places it at the final mating point and presses the “target” button to indicate the final mating point. Finally, the trunnion cap is connected to the moving payload trunnion to track the offsets between the moving trunnion and the mating point.

Spring tension keeps the belt straight and pulls the rotating part of the mechanical unit into an orientation along the offset vector of interest. Thus, the azimuth and elevation optical encoders provide data on the offset direction, while the reel optical encoder provides data on the offset radius. Finally, the technician can rely on the computer screen to visualize the payload movement.

The outputs of the optical encoders are fed to a portable computer, which is programmed with data-collection and user-interface software. The software includes components that implement the trigonometric formulas of transformation from spherical to Cartesian coordinates. The corresponding offset of displacement is displayed in Cartesian coordinates on the computer screen.

The mechanical unit fits within a 7.5 in (19 cm) cube. At a radial offset of ≅17 in (45.7 cm), this sensitive system can measure azimuth angles from 0° to 340°, accurate to within 0.3° and it can measure elevation angles from 10° to 100°, accurate within an average of 0.3°. The signals processed measure radius within an average of ≅0.03 in (0.76 mm). The basic system displays displacement for four trunnions but can be expanded to include as many as 20 mechanical units communicating with a single computer. The information displayed on the computer screen can be updated once per second.

An electromechanical apparatus for measuring three-dimensional offsets guides the signal processing system. To measure the offset of a nearby object, one simply stretches a spring-tensioned belt from the unit to the object.

To reduce the cost of operations, a simplified, robust, centrally operated, portable system could be developed to automatically take three-dimensional measurements of misalignments, display this information, and give the payload move conductor a recommendation for the next payload motion. Such a system could provide a universal foundation for fully automated, real-time, closed-loop control of payload transfer operations. Payload transfer operations also include transfers between a facility and the Orbiter Payload Canister. The proposed system is expected to be considered for use in future ground processing operations.

3.1 Commercial off-the-shelf systems Evaluated

Several commercial off-the-shelf (COTS) systems were evaluated during a trade studies process. The two-dimensional system shown in Figure 4a is more versatile, but it does not have the portability of the proposed system and therefore, was not a viable solution. The two-dimensional system shown in Figure 4b is mobile; but because of limited floor space, the payload's operational perimeter does not allow for this kind of mobile system.

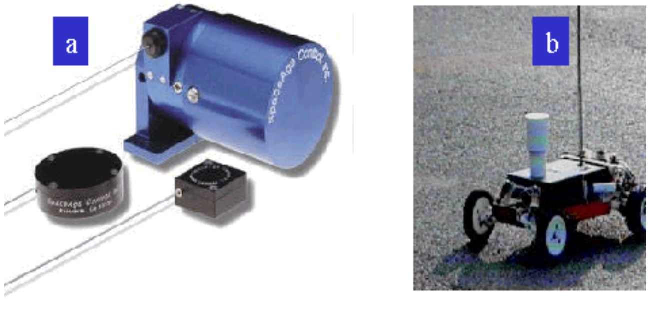

Figure 4. Two-Dimensional Sensor: (a) Fixed, (b) Mobile

The three-dimensional system shown in Figure 5a is almost as versatile as the proposed system. It is highly precise and portable, but it is expensive, costly to calibrate, and is currently not networked [6]. At the time of this study, the three-dimensional laser-guided system shown in Figure 5b was the most precise of all. However, it was not networked, and was not very portable. Despite being the most expensive and largest, it was the system eventually selected by the program.

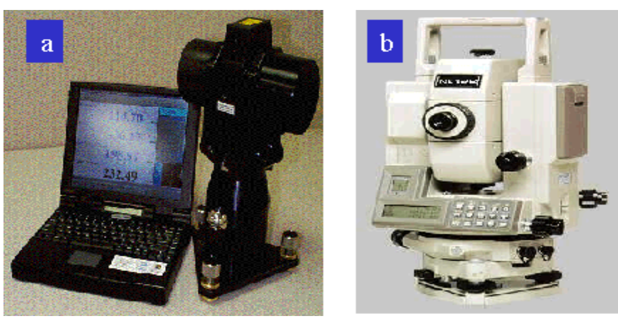

Figure 5. Three-Dimensional Sensor: (a) Portable, (b) Large

The three-dimensional Coordinate Measuring Machine (CMM) shown in Figure 6a is the most precise. The CMM is designed with a high-precision linear barcode device that rolls by means of an air-controlled mechanism, making the device easier to move. The CMM was used as a benchmark for testing the proposed system. However, it is not portable, it is extremely heavy, and it is not cost-effective. In addition, calibrating this machine is expensive [7]. Most of these calibrations are done by lasers such as the Renishaw's laser calibration system [8]. The accuracy delivered by these systems meets or exceeds the industry standard. The multi-axis measurement arm shown in Figure 6b is flexible, versatile, and accurate within ±0.0020 in. It weighs only 12 lb, but exceeds the required minimum width of 4 in. Another drawback is that it does not allow for networking of multiple units, although it can be used to verify point accuracies at specified reference points.

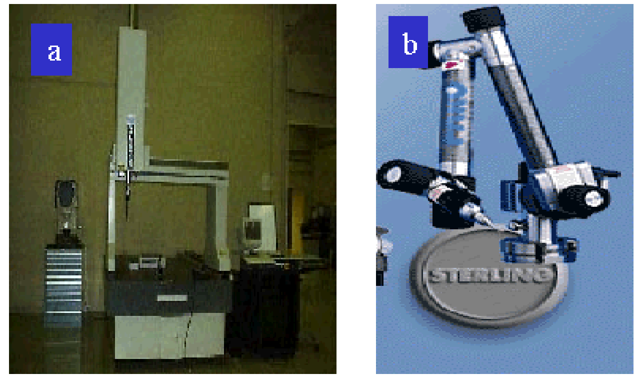

Figure 6. Three-Dimensional Sensor: (a) CMM, (b) Measurement Arm

3.2 Calibration System

The purpose of an electronic calibrating system is to enhance the measurement accuracy [9] of the Advanced Payload Transfer Measurement System's ground support equipment (GSE). It is composed of a sensor network subsystem, a network interface subsystem, and a user interface subsystem.

In the Space Shuttle Program, the method for payload transfer involved iterative, visually subjective, ruler-based manual measurements, calculations, and movements of the payload's position relative to the orbiter's cargo bay. In order to improve the accuracy of measurements and reduce the cost of operations, the use of an electromechanical system was investigated. Figure 3 shows an electromechanical unit that is positioned at each of the trunnion mating points. The accuracy of these networked sensors is superior to manual measurements.

However, this modular sensor unit system has some limitations. The mechanical part's accuracy is limited in the following spatial areas: elevation, azimuth, and reel range from the center axis of the measuring unit. Therefore, it is necessary to apply numerical analysis and filtering techniques to calibrate the system and compensate for the system's limitations. An algorithm that checks the values of the system is implemented by using least squares methods and its application to linear and nonlinear systems [10]. The resulting computation is compared against the coefficient of correlation to determine the validity of the approximation and accuracy of the system.

A timing belt, which is wound on a reel, is extended or retracted to obtain distance offsets. An electronic shift register, located as part of the measurement input device mechanism, processes counts, synchronized by a crystal oscillator, indicating the reel range measurement from the count decoder as shown in Figure 3. The electronic registers can process values for counts up to 65536 (±32768) or 2^{16}. These counts are converted to inches and cover a range of over 33 in. The use of this bounded range allows for better resolution in the sensor/signal detection system.

A quadrature decoder component incorporated in the digital input/output controller allows for better resolution. The decoder uses two channels, instead of one, to process digital counts. The embedded computer receives the commands given by the payload technician via buttons outside the electromechanical housing unit. In addition, the measurements are dependent upon the detecting mechanism, decoder sensitivity, and the external factors related to the reeling and unreeling of the timing belt tip [11]. An analog-to-digital converter input was located in the embedded microprocessor so that it can accept an optical mechanism in the future.

The method for measuring the distance to mating offsets depends on the accurate detection of the digital counter located in the pulley. The pulley releases the timing belt, which extends from the tip of the mechanical unit. The detecting mechanism does not consider external factors that cause errors during "linear" extensions [12]. For example, the timing belt, because of its own weight, tends to bend as it extends out. This means that the counting mechanism shows higher counts, which correspond to a range value that is disproportionately high. The error increases as the measured distance increases. A model of these deflections was designed and implemented to achieve more accurate results. More details about that implementation will be shown in Section 4.1.

3.3 Calibration Algorithm

A proposed calibration system is based on an inverse modeling scheme, shown in Figure 7 [11],

where,

x_i = reference data, (correct measurement from benchmark)

x_m = actual (inaccurate or uncorrected measurement

$\hat{x}_i$ = the output of the inverse adaptive filter (estimate of the correct measurement)

e = x_i - $\hat{x}_i$ = estimated error. (1)

An adaptive filter algorithm requires knowledge of the "desired" response to form the error signal needed (see equation 1) for the adaptive process to function. The reference data x_i contains the information used as the benchmark to compare the system's accuracy. The unknown system (our proposed system) contains sources of errors to be modeled by our design. Our model processes the data from x_m . Then the estimated calibrated measurement $\hat{x}_i$ is compared to the reference data so that the error can be further reduced. The output of the inverse adaptive filter $\hat{x}_i$ contains a smaller error than the one experienced by x_m . This error still needs to be corrected and ideally be minimized to 0. The implementation of this proposed adaptive method will optimize the measurements' accuracy and convergence. This recursive-like filtering structure, also referred as the equation-error base, guarantees stability during adaptation inherence.

4. THREE-DIMENSIONAL CALIBRATIONS

Process automation that employs digital signal processing has been developed for use in calibrations. A portable system that acquires signals reduces the need for people to communicate during payload positioning and measurement. The proposed system processes signals in real time by converting digital counts into Cartesian coordinates using English units and displaying them on a laptop screen.

4.1 Digital Signal Capturing and Conversion

Each of the electromechanical units, shown in Figure 3, has three sensors that detect: (1) the displacement of the timing belt released from the enclosed spool, (2) the elevation angle, and (3) the azimuth angle. The captured signals from each of these sensors serve as the input to each of the variables in the spherical coordinate system shown in Figure 8. The following resulting equations (2) thru (5) convert the displacement of the timing belt end to the Cartesian coordinate system [12].

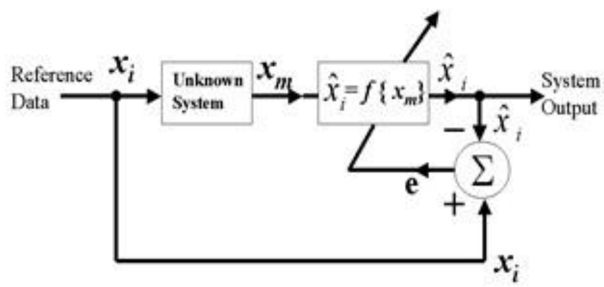

Figure 7. Adaptive Inverse Modeling Block Diagram

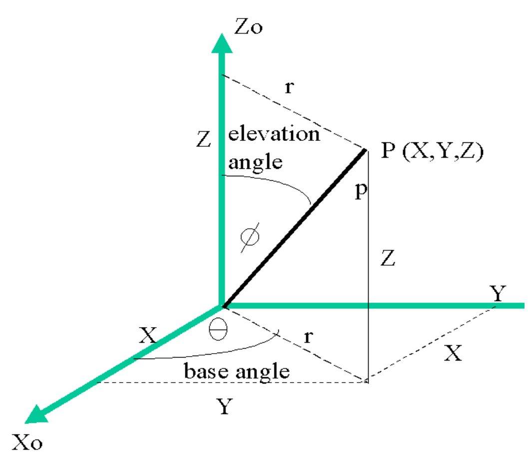

Figure 8. Distance Calculation from Spherical Coordinates

where:

ρ = distance projected in space
ϕ = elevation angle
θ = base angle
r = distance projected in the base plane
r = p[SIN(ELEVATION ANGLE)] (2)
X= p[SIN(ELEVATION ANGLE)] [COS(BASE ANGLE)] (3)
Y= p[SIN(ELEVATION ANGLE)] [SIN(BASE ANGLE)] (4)
Z= p[COS(ELEVATION ANGLE)] (5)

4.2 Detection of the Displacement of the Timing Belt

The retracting or the releasing of the system's timing belt causes a digital code wheel to spin around a decoding circuit that determines the direction of the displacement as well as the number of detected counts. If the timing belt is being retracted into the electromechanical unit, the direction of the code wheel will be counterclockwise. To calculate the linear displacement, each of the detected counts is automatically processed using the following conversion factor: 1 in (2.54 cm) = 1,257.912 counts.

The digital counts in the angular displacements are converted into the corresponding Cartesian coordinate values [13]. Therefore, the spherical coordinates with values (ρ = 10.996, θ = 180°, and ϕ = 45°) correspond to the following values in the Cartesian coordinates: (X = $^{+}$7.775, Y = $^{-}$7.775 and Z = $^{+}$7.775).

The programming of the count-to-angle conversion is more efficient when it occurs at the GUI level. Modifications to the calibration system can be made easier at this level rather than at the microcontroller level because, at the microcontroller level, the Electrically Erasable Programmable Read-Only Memory (EEPROM) will have to be software-burned and reprogrammed whenever the system needs to be recalibrated.

4.3 Detection of the Elevation Angle

As the electromechanical unit's timing belt is lifted, the mounted code wheel rotates counterclockwise. This angular motion determines the position of the trunnion with respect to the referenced point of arrival. The resolution of this code wheel is highly sensitive. Normally, the number of counts for this encoder is 1,000. However, by combining the two channel signal states, the sensitivity of the detecting signal increases by a factor of four. There are 4,000 possible counts around the circumference of this one-inch-diameter code wheel.

The quadrature decoder circuitry imposes a second timing constraint between the external clock and the input signals. There must be at least one clock period between consecutive quadrature states. A quadrature state is defined by consecutive edges on both channels. Therefore, the encoder state period deviations must be greater than the clock state period to obtain proper deviations from the nominal 90^{o} phasing of input signals [14].

Therefore, instead of having two states, "on" or "off" for one channel, there will be a combination of these states for two channels, which increases the number of states considered during signal counting.

4.4 Detection of the Azimuth Angle

The techniques for detecting the base angle are similar to those used to detect the elevation angle as described above. However, the two signal processing methods use wires as the transmitting media. These wires are routed from the top of the unit down to the base axis of the electromechanical unit. The 2-in (5.08 cm) encoder wheel is mounted on the base axis. The larger code wheel is necessary because of the design constraint of the electromechanical system. The width of the base conduit allows for easier rotation of the mechanical unit by creating less torque friction from the wires running through this medium.

The azimuth angle has a limited range of around 350°. This angular signal detection determines the base coordinates of the moving payload with respect to the established reference. Every one of the 4,000 counts is equivalent to an angular rotation of 360°/4,000 or a resolution of 0.09° per digital signal count.

5. PERFORMANCE

Testing scenarios were performed, leading to linear and nonlinear characterization of the reel displacement at various distances. The uncorrected or actual measurement detected by the system in inches was compared to the estimated correct value [15]. The measured errors were considered and minimized using proven numerical analysis techniques.

5.1 Test Results for the Reel Displacement

The counter's raw data was supplied to the calibrating algorithm. Figure 9 compares the uncorrected and the corrected values obtained from testing. The correlation coefficient between the ideal and measured values was found to be 0.9999 for the least square fitting from the original data.

Before this calibration scheme was implemented, the electromechanical system was able to take measurements within an accuracy of 0.080 in. The values obtained from the algorithm were compared with the values obtained from the benchmark. The benchmark, the Coordinate Measurement Machine, had a calibrated error of 50×10^{-6} in [16].

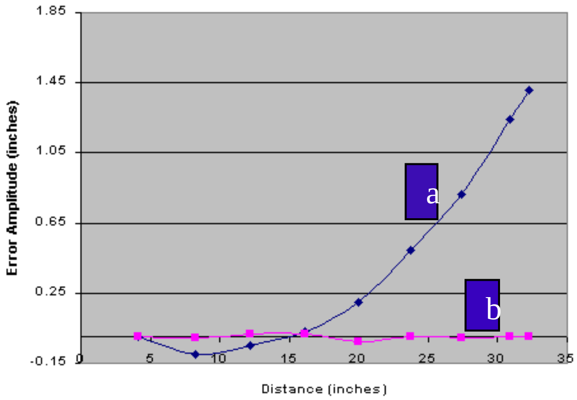

Figure 9. Measurements Error Curve: (a) Before Correction, (b) After Correction

The proposed algorithm was found to improve the accuracy of the reeling range measurements by nearly 50%, yielding an accuracy of better than 0.055 in. The average error was found to be 0.013918 in [17]. Thus, the proposed algorithm improved the electromechanical system's accuracy and brought it within the acceptable range. The same methodology is applied for the elevation and azimuth angle measurements. Figure 9 shows how the proposed calibration scheme improved the parabolic error and minimized the error down to a polynomial interpretation.

5.2 Accuracy of the Measured Signal

Once the digital signal is processed, there must be an algorithm that verifies the validity of the position of the timing belt end. A calibration technique has been shown to work for this system in order to keep the system's accuracy to within an error of less than 0.055 in (0.1397 cm). Figure 10 displays the timing belt linear error at distances up to 33 in from the center of the electromechanical unit. Additionally, the implementation of polynomial equations dramatically improved the accuracy of measurements during data analysis.

Some of the known errors seen during measurement readings are caused by the human interpretation. A payload coordinator must visualize the rotation of a moving payload. A payload rotation consists of a pitch, yaw, and roll. Judging the next payload move by only looking at a 2-dimensional view is not enough for coordinating a safe payload transfer. Determining the pitch, yaw, and roll orientation of a moving payload is similar to the function performed by the space shuttle's attitude coordinate system.

Further analysis of this calibration scheme can be conducted when the reel, azimuth, and elevation count inaccuracies are minimized [18].

5.3 Safety Enhancement

To reduce operational hazards during any transportation activity, adequate safety precautions must be taken. Some of the activities that take place during the ground processing of space launch vehicles deal with the placement of payloads into the cargo bay and the transport of those payloads. A proposed wireless measuring system is one method to be considered for use in these hazardous activities.

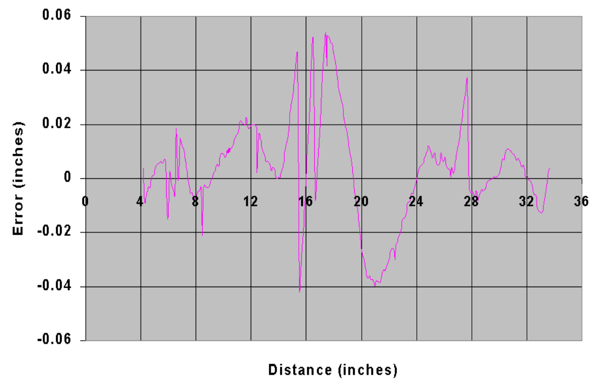

Figure 10. Corrected Error vs. Reel Range Distance

This portable data acquisition system will certainly improve the manual calculations of the actual payload position with respect to the mating points. This system will also calculate, estimate, and notify the payload conductor of the next move to be coordinated with the crane operator.

Normally, this Advanced Payload Transfer Measurement System (APTMS) will use the network of sensors to determine the position of the payload. This networking communication is made possible by the portable computer's RS-232 port and an RS-485 port for communication at longer distances. This method requires a cable to interconnect the portable computer port and the network of sensors. This system offers the capability to upgrade this network interconnection into a wireless data communication. The advantages in using this methodology are that it reduces the number of cables used around the moving payload transporter while increasing the distance from the networked sensors. Having fewer elements around the transporter will reduce the risk of a mishap occurring.

The APTMS meets applicable KSC safety design requirements as well as those of the Occupational Safety and Health Act. The design and use of the APTMS (e.g., its use of glass encoder wheels and mercury cells) complies with KSC standards. The failure of any APTMS GSE item does not degrade the inherent safety of equipment or systems being supported. An APTMS GSE failure does not create a hazardous condition, injure employees, or damage or degrade the orbiter or its payload. All APTMS GSE is designed to be "fail-safe" wherever a single failure would be harmful to employees or hardware. The nature of the APTMS application does not require hazard proofing.

6. CONCLUSION

This paper presented the development of a design for an Electronic Ground Support System (EGSS) for NASA's payload transfer operations. This EGSS is a self-calibrating, simple, robust, centrally controlled system for potential use in payload-transfer operations that are hazardous and time-consuming. Because scientists and engineers in many different disciplines have been involved in the development of this system and in its technical support, intensive multidisciplinary work was instrumental in successfully completing the program. This study introduced a three-dimensional real-time data acquisition system based on a knowledge-based approach, and illustrated how an automated data acquisition system can be used to enhance the overall performance of payload transfer operations while involving resources from many disciplines. This system has improved and exceeded its accuracy requirements, contained a more convenient man-machine interface, and showed how safety could be improved. All aspects of the proposed improvements have been confirmed using field test results. New space programs that require transferring of payloads during ground operations, may benefit from the research and development achieved by this electromechanical system.

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