Unique Investigation Technical Assistance by the Manufacturer
Eric J. East and John D. Miller – The Boeing Company

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Introduction

Technical assistance from airplane manufacturers and other technical advisers to accident investigation authorities is common practice during ICAO Annex 13 investigations. The type of assistance offered typically deals with technical and procedural evaluations which might include laboratory examinations or flight simulator work mostly with in-person participation. The topics discussed in this paper represent recent unique techniques and engagements that took place with Boeing technical assistance. Topics include a Boeing scientific imaging produced 360 degree virtual reality tour of the NTSB wreckage reconstruction for Atlas flight 3591 and Systems Integration Laboratory testing to experience and witness 777 pilot control mechanical elements beyond those found in conventional simulators. The assistance provided helped accident investigation authorities gain a deeper understanding of technical and operational undertones of the related events and helped to grow the knowledge of investigators in a collaborative hands-on environment.

Atlas Air Flight 3591 Accident – NTSB Wreckage Recovery and Reconstruction

On February 23, 2019 Atlas Air flight 3591, a 767-300 Boeing Converted Freighter (BCF), impacted a marshy bay area (Trinity Bay) about 40 miles southeast of George Bush Intercontinental Airport near Houston, Texas. The main debris field (Figure 1) extended about 350 yards in length and 170 yards in width beyond the initial impact point.[1] While almost all the airplane wreckage was located in the main debris field the wreckage was highly fragmented and scattered. The water was 0 to 3 feet deep in the main debris field depending on the tide and wind conditions and much of the wreckage was buried up to 10 feet deep in soft mud.

Figure 1 – Main Debris Field (Photo: NTSB)

Figure 2 – Debris Field Excavation (Photo: NTSB)

Initial recovery efforts involved a hand search in the mud for the flight data and cockpit voice recorders after use of Underwater Locator Beacon (ULB) locating equipment provided by Boeing was determined to be ineffective in the shallow water and soft mud environment. The flight data and cockpit voice recorders were eventually recovered via the hand search method after about a week long effort.

Larger portions of wreckage were recovered and staged on barges using airboats and cranes from a recovery contractor (Figure 2). Excavation of the debris field followed using specialized screens fitted to excavator buckets that would allow the water and mud to drain while retaining wreckage larger than about 4 inches in size. A grid system was used at the site to ensure complete excavation coverage of the main debris field. Excavation efforts continued for about 6 weeks concurrent with storage and reconstruction efforts described below.

The wreckage recovered from the excavation activities were collected in about 200 Tyvek bags with an average bag weight of 500 pounds. Recovered wreckage was transported to a storage location at a warehouse nearby. A portion of the warehouse measuring 200 feet by 190 feet was chosen for storage. The first load of recovered wreckage arrived at the warehouse on March 4. Wreckage continued to be delivered to the warehouse as it was recovered until April 12. Local authorities collected floating debris and cargo that was recovered up to 20 miles away from the debris field and transported them to the warehouse.

The NTSB decided to lay all of the identifiable debris on the floor of the warehouse in a two dimensional reconstruction. The floor was measured and taped with specific locations for the fuselage, wing upper and lower surfaces, horizontal stabilizer upper and lower surfaces, vertical stabilizer and rudder, engines, systems components, center wing structure, cargo handling components, rigid cargo barrier, and flight deck components. The grid was set up using defined fuselage station and stringer locations with a 10% expansion to allow for wreckage deformation and personnel movement. Each identified piece of wreckage placed in the reconstruction layout was given a unique identifier and catalogued including photos and identifying information. The reconstruction effort was continuously staffed between March 4 and April 12, 2019 by the NTSB with the support of party members from Boeing, the airline, the airline pilot union, and the FAA.

Boeing Assistance with Wreckage Reconstruction

Boeing technical experts from air safety investigation, structures design engineering, structural stress analysis, service engineering, and production liaison engineering participated in the wreckage reconstruction at the request of the NTSB. These individuals were key to identifying and placing systems, structures, and powerplant fragments that could not be identified by part / serial numbers or data tags alone. They used their broad knowledge of unique design and material features and were aided in some cases by information such as the external paint livery to create a digital map[2] of the recovered identifiable wreckage such as the fuselage in Figure 3.

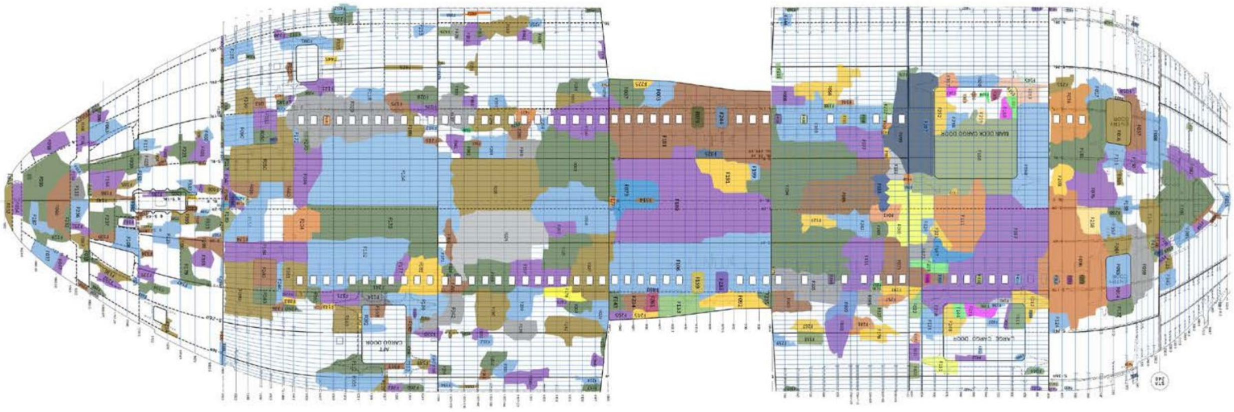

Figure 3 – Fuselage Wreckage Map (Image: Boeing)

NTSB UAS Wreckage Reconstruction Image Capture

The NTSB utilized several techniques for photo-documenting the accident site and reconstruction. The NTSB's UAS Team acquired high-resolution aerial imagery of the wreckage reconstruction (using two small UAS inside the warehouse) and processed it using commercially available photogrammetry software to develop a three-dimensional model[3] of the reconstruction an overview of which is shown in Figure 4. A full georeferenced orthomosaic map and 3-dimensional point cloud of the reconstruction were created.

Figure 4 – UAS Aerial Image of Reconstruction (Image: NTSB)

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Boeing 360º Virtual Reality Tour of Wreckage Reconstruction

The NTSB asked party members for input regarding any additional image capture methods beyond that of traditional photography and UAS photogrammetry. The NTSB was made aware of several Boeing image capture capabilities and techniques used in a variety of in-service customer support as well as the test and production environments. The Scientific Imaging team at Boeing executes a variety of these image capture methods within the company in areas that include wind tunnel testing, material testing, full scale static testing, interior and flight deck configurations, 360º virtual reality tours, high speed video capture, infrared imaging, as well as in-flight testing and certification imagery. Ultimately the NTSB determined that 360º degree virtual reality tour method would be beneficial to their investigation.

The Advanced Photographic Engineering eXperience (APEX) team within Boeing Scientific Imaging develops interactive recorded views and other contextual visualization tools that utilize high quality 360º images. These tools are integrated with quality, manufacturing, and engineering data in the factory environment for virtual and augmented reality applications such as automated build quality maps and 3D model alignments when connected with production data. Boeing has advanced the state of the art of 360º imaging by localizing spherical images with model based engineering, allowing for advanced capabilities such as referencing the 'as-built' aligned to the 'as designed' model based definition. Many other teams within Boeing leverage these virtual reality tour methods such as airline virtual maintenance training and airplane on ground (AOG) damage surveys which are captured in field locations outside of the factory environment. Boeing has also benchmarked our methods with 360º virtual tour methods from others such as the FBI Evidence Response Team (ERT) that utilize 360º spherical video and photography for forensic investigations in both indoor and outdoor environments.

A photographer from the Boeing APEX team traveled to the Atlas flight 3591 wreckage storage location when the reconstruction efforts were complete. The photographer acquired high-resolution 360° images at 66 locations within the wreckage reconstruction layout using a tripod mounted DSLR (Digital Single Lens Reflex) camera with a calibrated panoramic nodal attachment and a wide angle lens. Image capture was completed in less than 8 hours. The camera setup was moved throughout the reconstruction layout and images were captured at key locations around the periphery and within the layout area. These locations were georeferenced and integrated with the NTSB UAS imagery. The images were later processed into a 360º virtual reality tour of the reconstruction and provided to the investigation as shown in Figures 5 and 6.

These documentation methods preserved the wreckage reconstruction in a highly accurate, digital format. Due to the high resolution and detailed image processing, the catalogued unique identifiers are visible and legible in the virtual tour images. This provided investigators useful information that could be referenced or considered throughout the investigation in other follow-on work such as the system component examination for the thrust lever assembly[4] shown in Figures 7 and 8. Beyond the benefits to the investigation, this format can also be used in immersive training so future investigators can gain knowledge in wreckage reconstruction best practices.

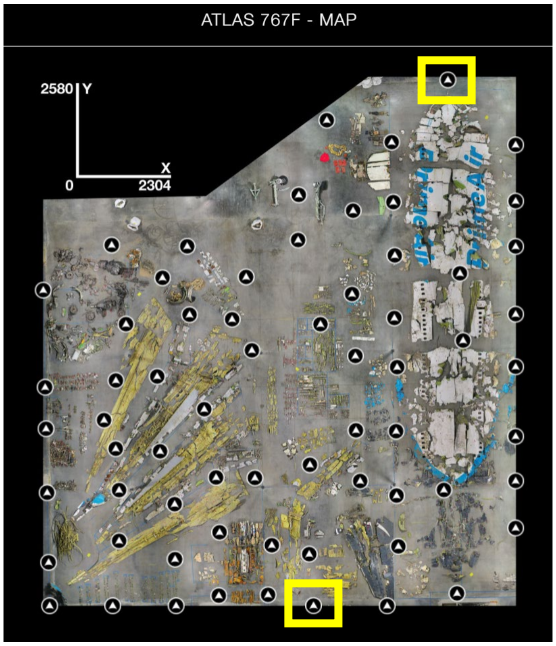

Figure 5 – Virtual Tour Map (Fig 6 Viewpoints shown) (Image: Boeing)

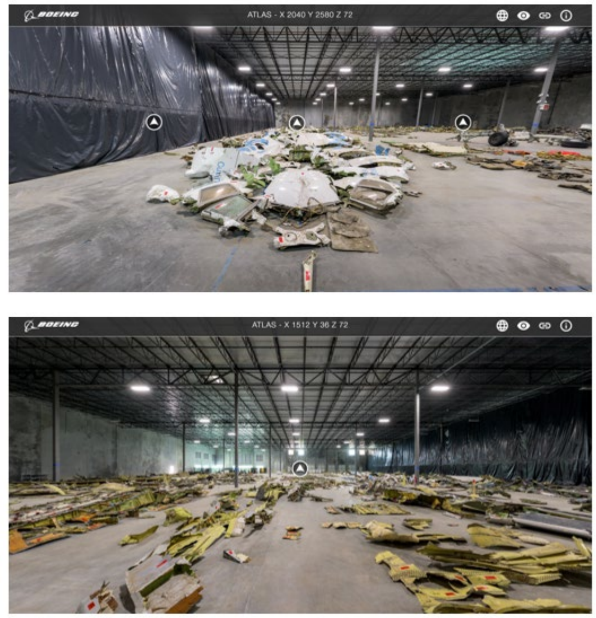

Figure 6 – Virtual Tour Viewpoints (Images: Boeing)

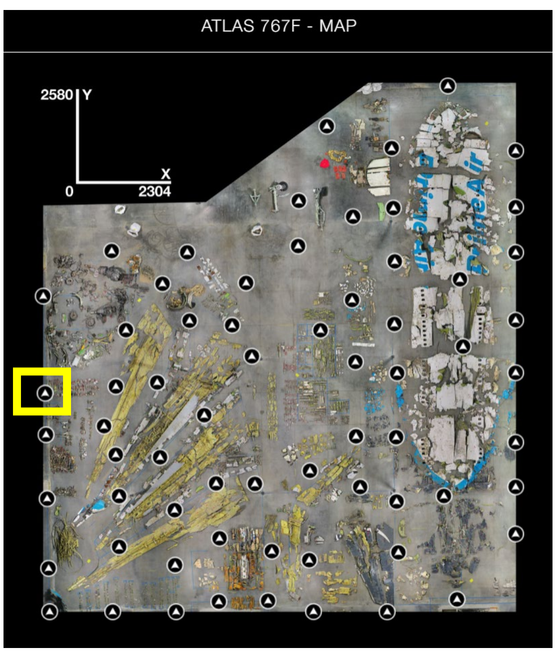

Figure 7 – Virtual Tour Map with Systems Area Highlight (Image: Boeing)

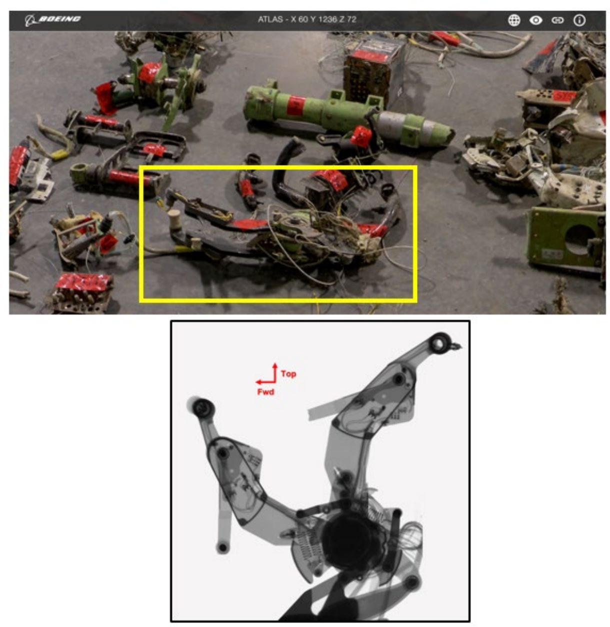

Figure 8 – Thrust Lever Assembly in Reconstruction and Digital X-Ray Composite (Images: Boeing)

This effort represented the first use of these Boeing imaging methods during an NTSB investigation. This virtual tour method is not restricted to indoor use and has been used in outdoor and remote field settings within Boeing including inside more intact airframe structures. Image capture can be accomplished by professional photographers or if there are limitations in the number of investigation participants at a given accident or reconstruction site, Boeing air safety investigators trained in the method can travel to the site with minimal camera equipment. As shown in the Atlas flight 3591 reconstruction, image capture can take place in a minimal amount of time with relatively common unobtrusive camera equipment. Post processing and integration with other information and imagery can provide a powerful contextual visualization that can be created concurrent to investigation activities in the field. As 360^{o} imagery is commonplace within society in areas such as real estate, education, and media, interfaces can be created that are intuitive to interact with. This reconstruction example shows that 360^{o} virtual reality imaging in accident investigation can be a useful stand-alone method or it can be used to enhance other imaging methods at an accident/incident site or reconstruction effort. Boeing has broad experience in these methods and how they relate to the products they manufacture and can be a knowledgeable resource to investigators for this imaging technique.

Serious Incident Investigation Support at 777X Systems Integration Laboratory

A serious incident investigation in France led to a greater understanding of 777 pilot controls beyond the traditional use of flight simulators. Boeing hosted investigators from the BEA, NTSB, and FAA at the 777X Systems Integration Laboratory in Seattle, WA, as shown in Figure 9, to experience pilot control mechanical elements and environmental visuals for multiple scenarios of interest in lieu of a conventional flight simulator using control loader devices. A review of the flight data recorded from the serious incident in France noted that simultaneous and opposing flight control inputs by each pilot were observed during a go-around while on approach to the destination airport.[5] The investigation team was interested in evaluating the mechanical breakout features common in linked pilot controls on Boeing aircraft, and therefore, the mechanical flight controls present within the laboratory provided an opportunity to observe the hardware in use rather than simulated behavior produced by control loaders.

The 777X Systems Integration Laboratory in was in-part built using existing 777-200 pilot control hardware, production line number 30 (originally delivered in 1996), by removing the forward section of the aircraft as shown in Figure 10. Boeing has historically developed Systems Integration Labs across multiple commercial test programs as a method to better integrate and test systems and subsystems before, during, and after flight testing. Because the 777X Systems Integration Laboratory included the same mechanical breakout features from the 777-200 that were also present in the incident aircraft, a 777-300ER, Boeing was able to develop test conditions specific to the interests of the investigation team.

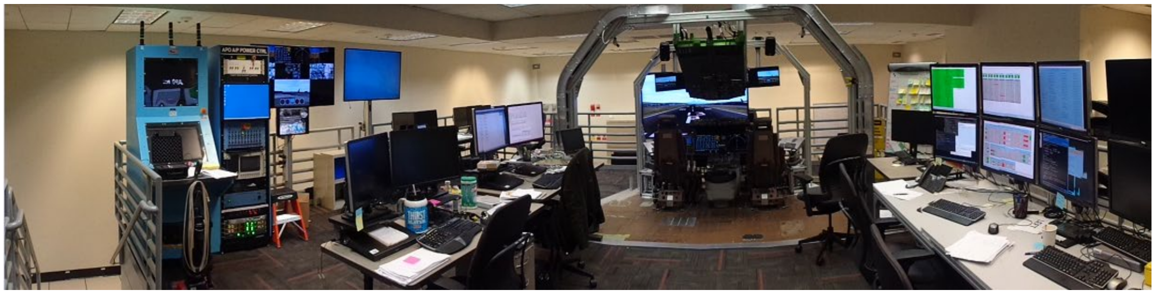

Figure 9 - Boeing 777X Systems Integration Laboratory (Images: Boeing)

Figure 10 - 777-200 Line Number 30 Forward Section Removal (Images: Boeing)

777 Pilot Control Overview

The 777 pilot controls use a conventional scheme of control columns for pitch (elevator system), wheels for roll (lateral system), and pedals for yaw (rudder system) as shown in Figure 11, and the associated hardware from the 777-200 was transferred to the Systems Integration Laboratory as shown in Figure 12. The real pilot controls were slightly modified to accommodate testing on a 777X configuration. The pilot control sensors are connected to the actual 777X Integrated Flight Control Electronics (IFCE) system containing four Actuator Control Electronics (ACEs) and three Flight Control Modules (FCMs). While all control surface actuation is simulated, the control laws and force feedback are fully represented within the lab thereby providing the actual mechanical control feel of a 777 airplane. By comparison, a conventional flight simulator equipped with control loader devices utilizes a simulation model representative of the forward pilot control system forces rather than the physical hardware.

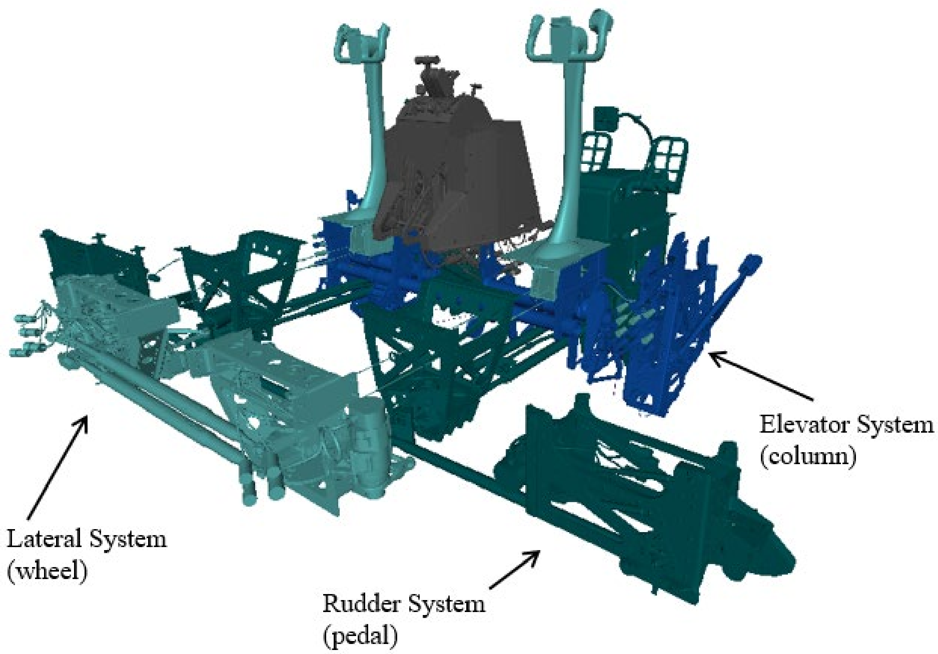

Figure 11 - 777 Pilot Controls (Images: Boeing)

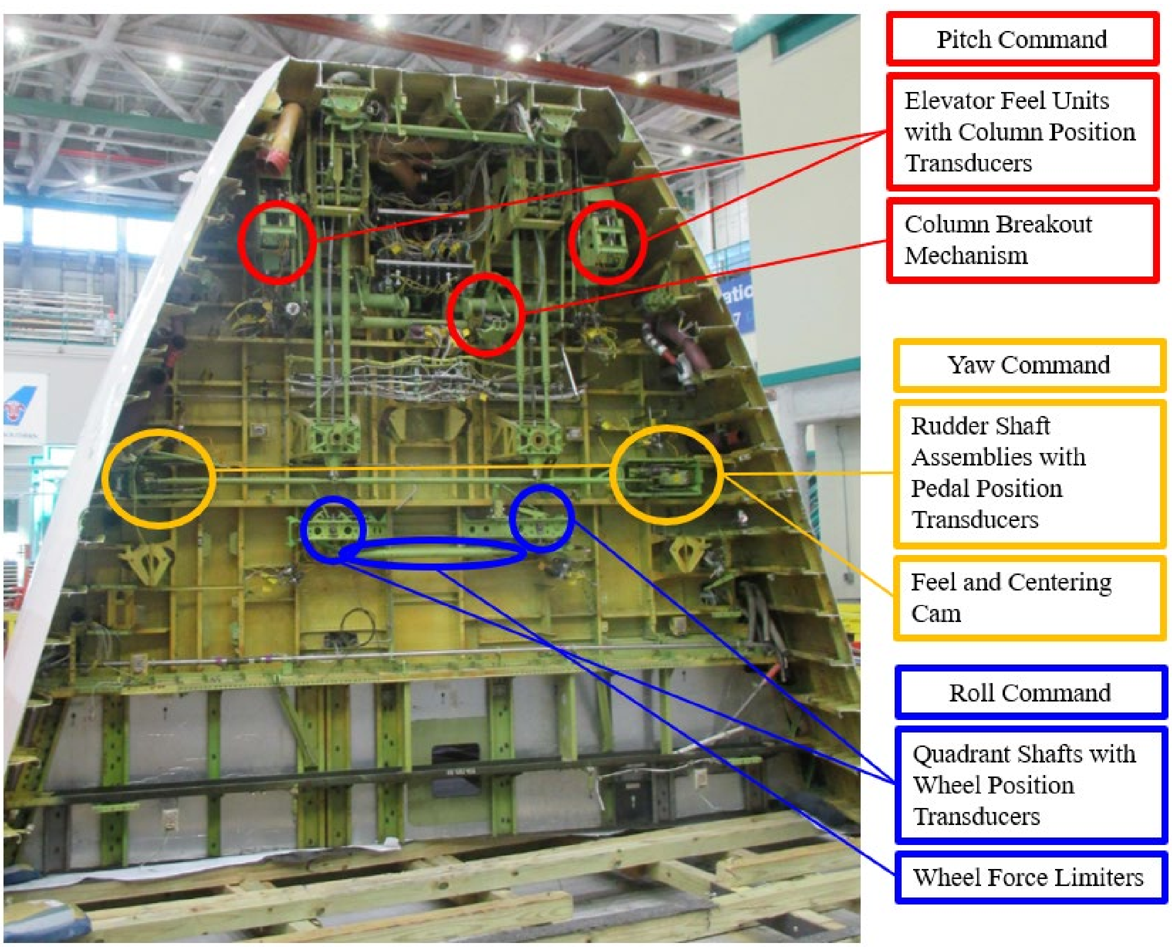

Figure 42 - 777-200 Hardware Removal for the 777 Systems Integration Laboratory (Images: Boeing)

For pitch command, six Linear Variable Differential Transformers (LVDT) sense column position and are distributed across the left and right seat elevator feel unit assemblies. The variable elevator feel function provides variable artificial feel forces through two independent mechanical units. These two feel units are connected to each other by a bus shaft that further provides a means to mechanically override a flight control jam when present. See red highlights in Figure 12.

For roll command, six LVDTs sense wheel position and are distributed across the left and right seat quadrant shafts. Fixed aileron feel and centering forces are provided using a cam and roller unit, and the quadrant shafts are connected through force limiters to provide jam override functionality. See blue highlights in Figure 12.

For yaw command, four LVTDs sense rudder pedal position across the left and right shaft assemblies. Yaw control feel and centering forces are transmitted through a single cam and roller unit. See yellow highlights in Figure 12.

Boeing conducted an airplane performance evaluation with recorded data obtained from the event airplane to help assist the investigation in determining the sequence of events and pilot inputs that occurred over the course of the event. Having access to the actual pilot control hardware in a lab setting allowed the investigation to gain knowledge beyond the recorded parameters by conducting simulated pilot control operational conditions on a fully integrated flight control system. The lab setting provided a safe and efficient means to gain access to the hardware while in operation without the time consuming and resource intensive effort to secure an in-service or test aircraft with instrumentation. Of particular value, several investigative team members were able to position themselves under the test rig and visually monitor the pilot controls in motion during operational conditions both on-ground and in-flight. This helped provide a more thorough understanding of the 777 pilot control system design while documenting and assessing both qualitative and quantitative data real time with a diverse group of investigators. Approximately forty separate conditions, repeated as necessary, provided observations in oppositional control inputs, flight control sweeps, jammed controls, and autopilot override. Figure 13 provides an example of recorded data obtained from exercises performed in the 777X Systems Integration Lab.

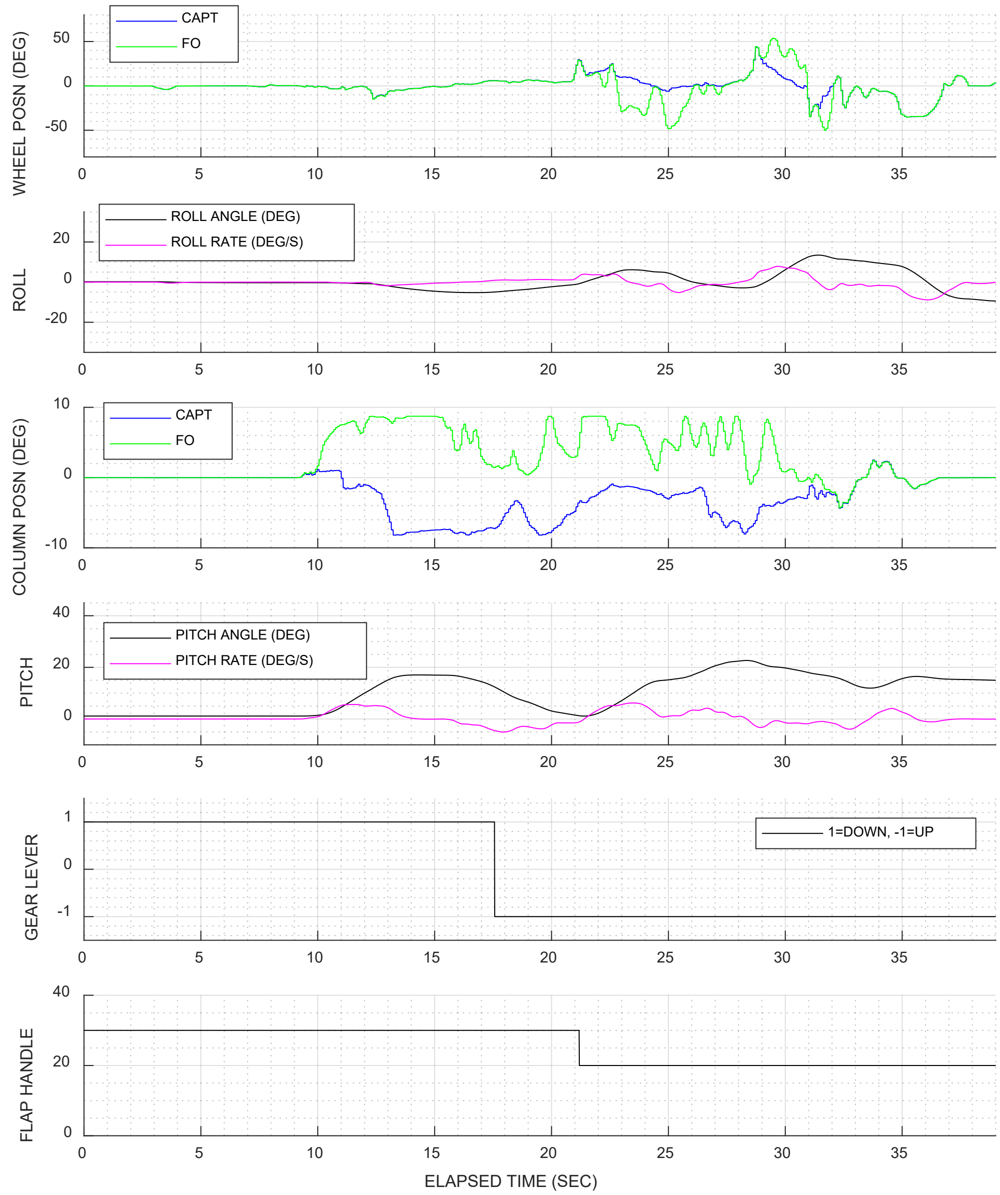

Figure 53 - 777 Systems Integration Lab Oppositional Control Input Exercise (Images: Boeing)

This effort at 777X Systems Integration Laboratory highlights the collaborative nature of technical assistance that an aircraft manufacturer like Boeing can provide as a technical adviser to an ICAO Annex 13 investigation. The technical and operational understandings derived from the use of actual aircraft hardware in an integrated and controlled lab setting can provide an alternative to potentially time consuming and disruptive on-aircraft testing. This can also help expedite the investigative process when there is a constraint on resources available. Boeing remains committed to working with safety investigation authorities to find resources that will support a robust and thorough ICAO Annex 13 investigations.

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(1) DCA19MA086 NTSB Structures Group Chairman's Factual Report, dated October 29, 2019
(2) DCA19MA086 NTSB Structures Group Chairman's Factual Report Appendix A – Figures, dated October 29, 2019, page 10
(3) DCA19MA086 NTSB Structures Group Chairman's Factual Report Appendix A – Figures, dated October 29, 2019, page 9
(4) DCA19MA086 NTSB Systems Group Chairman's Factual Report - Attachment 2 - Boeing Commercial Airplanes Equipment Quality Analysis Report - Examination Of Control Stand Thrust Lever Assembly, dated 02 December 2019
(5) BEA Press Release, "Safety Investigation Into The Serious Incident To The Boeing 777 Registered F-GSQI Operated By Air France On 5 April 2022 At Charles De Gaulle Airport -Investigation Update-", dated 27 April 2022

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