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FLIGHT TEST EXPERIENCE AND CONTROLLED IMPACT
OF A LARGE, FOUR-ENGINE, REMOTELY PILOTED AIRPLANE

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ABSTRACT

NASA Ames Research Center's Dryden Flight Research Facility and the Federal Aviation Administration conducted the controlled impact demonstration (CID) program using a large, four-engine, remotely piloted transport airplane. Closed-loop primary flight control was performed from a ground-based cockpit and digital computer in conjunction with an up/down telemetry link. Uplink commands were received aboard the airplane and transferred through uplink interface systems to a highly modified Bendix PB-20D autopilot. Both proportional and discrete commands were generated by the ground pilot.

Prior to flight tests, extensive simulation was conducted during the development of ground-based digital control laws. The control laws included primary control, secondary control, and "racetrack" and final approach guidance. Extensive ground checks were performed on all remotely piloted systems. However, manned flight tests were the primary method of verification and validation of control law concepts developed from simulation.

This paper discusses the design, development, and flight testing of control laws and systems required to accomplish the remotely piloted mission.

NOMENCLATURE

AMK	antimisting kerosene
CID	controlled impact demonstration
CSMC	computer select mode control
c	autopilot elevator servo model gain
EGT	exhaust gas temperature
h	altitude, m (ft)
ILS	instrument landing system
K, K_2	autopilot elevator servo model gains
K_p, $K_{\phi c}$	roll control system gains
K_q, $K_{\phi trim}$	pitch control system gains
K_t, K_{ttrim}	throttle control system gains
K_x, K_{nws}	yaw control system gains
MLS	microwave landing system
MSL	mean sea level
PCM	pulse code modulation
RPV	remotely piloted vehicle
SIBLINC	scale, invert, bias, logic, interface console
s	Laplace transform operator
T_{max}	autopilot elevator servo model maximum allowable torque
V_{ref}	autothrottle reference airspeed, knots
X	X position relative to runway, m (ft)
Y	Y position relative to runway, m (ft)
ζ	damping ratio
θ	pitch angle, deg or rad
τ	time delay, sec
ϕ	bank angle, deg or rad
ψ	heading angle, deg or rad
ω	frequency, rad/sec

Subscript·

cas	calibrated airspeed

INTRODUCTION

The National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) conducted a joint program for the acquisition, demonstration, and validation of technology for the improvement of transport aircraft occupant crash survivability using a large, four-engine, remotely piloted transport airplane in a controlled impact demonstration (CID). The CID program was conducted at the NASA Ames Research Center's Dryden Flight Research Facility (DFRF), at Edwards, California, and was completed in late 1984. The objectives of the CID program were (1) to demonstrate a reduction of post-crash fire through the use of antimisting fuel, (2) to acquire transport crash structural data, and (3) to demonstrate the effectiveness of the existing, improved seat/restraint and cabin structural systems.

The airplane used in the CID program, a four-engine Boeing B-720 jet transport manufactured in

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the early 1960s, typifies jet transport aircraft of that era. This airplane was nearing the end of its useful life when it was transferred to NASA by the FAA for use in the CID program. Extensive modifications were required to convert this airplane from a manned (crew of three) to a remotely piloted vehicle (RPV) while retaining the manned capability for RPV checkout. Extensive instrumentation was also added to support each of the various experiments, and a limited amount was added for the RPV system.

The crash scenario was representative of a survivable accident, such as could occur following a missed approach or takeoff abort. The precise requirements of the antimisting kerosene (AMK) and crashworthiness experiments of the CID mission dictated very tight constraints on impact parameters such as airspeed, sink rate, pitch angle, and impact location. The airspeed, sink rate, and pitch angle were selected to maintain fuselage integrity during acquisition of longitudinal and vertical acceleration data. Combining all of the CID experiment requirements into one flight resulted in a set of design goals for impact conditions, listed in Table 1. It was further specified that the impact would be with the landing gear in the retracted position, with the flaps at 30°, and with a maximum amount of fuel aboard.

Predetermined program ground rules dictated that above an altitude of 122 m (400 ft) any of the specified major experimentors could call a mission abort or go-around if their equipment suffered a major failure, and below 122 m (400 ft), only the project pilot could call an abort or go-around. Below 45.7 m (150 ft) the airplane was committed to impact, because it was at this point that the onboard data recorders and cameras were activated.

Figure 1 shows the layout of the crash site. The triangular obstacles are "wing cutters," designed to open wing fuel tanks to ensure dispersal of AMK. The heavy horizontal line was a fence 2.4 m (8 ft) high, made of frangible material which aided the RPV pilot in the targeting task. Where the centerline intersects the fence, a bright orange panel was placed to provide the RPV pilot a visual guidance aimpoint.

The DFRF, with its unique facilities, capabilities, and extensive RPV experience, was selected to

1. prepare the test airplane and associated experiments for the final mission,

2. design and implement all RPV systems for this test,

3. conduct all manned RPV checkout test flights, and

4. conduct the final impact mission.

This paper discusses the design, development, and flight testing of the systems required to accomplish the remotely piloted mission and presents a summary of the final mission.

AIRPLANE DESCRIPTION AND FLIGHT TEST PROCEDURE

Airplane

The Boeing B-720 airplane is a swept-wing, swept-tail, four-engine, medium-range jet transport. The principal physical dimensions of the B-720 are shown in Fig. 2. The approximate empty weight was 44,490 kg (98,000 lb) with a structural design gross weight of 92,160 kg (203,000 lb).

Primary flight controls were ailerons, elevator, and rudder. The ailerons and elevator were controlled by aerodynamic tabs and assisted by aerodynamic balance panels. The rudder was hydraulically powered and assisted by aerodynamic balance panels; however, a manually operated aerodynamic tab backup was provided.

The outboard ailerons were designed to stay in the faired position with the flaps retracted and then to operate with increasing authority as a function of increasing flap deflection. Upper wing surface spoilers augment roll control with the inboard ailerons, and also operate as speed brakes. Double-slotted flaps and leading-edge flaps provide lift and drag control for slow-speed flight.

Pitch trim was accomplished through a variable-incidence stabilizer. Roll and yaw trim were operated through aileron and rudder, respectively.

For the CID program, the Bendix PB-20D autopilot was modified and used to operate as the primary RPV flight control. Unused portions of the autopilot were deactivated as a part of the modification for remotely piloted operation to eliminate potential failure points.

Flight Test Procedure

The primary approach used in the checkout of the B-720 RPV systems was manned flight tests. Both the onboard pilot and copilot were provided with a disengaging switch which was located on their cockpit control wheel. This switch was capable of disengaging all RPV system functions.

Prior to the final CID mission, a total of 14 manned test flights were made during which 10 remote takeoffs, 13 remote landings, and 69 CID approaches were accomplished. All manned remote takeoffs were flown from the Edwards main runway with the remote landings taking place on the emergency recovery runway.

The actual CID mission profile and boundary are presented in Fig. 3. The takeoff runway was lakebed runway 17 on Rogers Dry Lake. Following takeoff, the vehicle would make a gentle left-hand turn until it intersected the racetrack at approximately 700 m (2300 ft) above ground level (AGL) which was 1400 m (4600 ft) mean sea level (MSL). With the airplane level and on the racetrack, a right turn with a radius of 1.4 n. mi. was performed with a rollout on the impact runway heading. Final-approach glideslope guidance was

initiated at the heading intercept point which was approximately 5.6 n. mi. from the impact point.

In the event that the final mission had to be aborted, the emergency recovery runway (runway 25) at the south edge of the lakebed would have been used.

The terminate boundary is shown as the light boundary on the outside of the buffer (darker) boundary. If for any reason the aircraft strayed outside the buffer boundary, a terminate command would be transmitted through an independent system. This command consisted of a full nose-down stabilizer, right rudder, engine fuel shutoff, and gear down to insure that the vehicle would impact within the sterile area indicated by the terminate boundary.

CID RPV SYSTEMS

Systems Overview

During manned RPV checkout flights, flight crew safety was of primary concern. Therefore, it was necessary that the remotely piloted capability be developed while insuring the integrity of the conventional onboard piloted control system. The existing Bendix autopilot had the capability of receiving instrument landing system (ILS) radio signal command inputs to the elevator and aileron channels. Replacing the ILS radio signal command paths with uplinked elevator and aileron command signals provided the basic RPV capability. Rudder pedal commands were added to the basic parallel yaw damper. The autopilot retained its attitude-hold feedback paths so that only uplink commands from the ground were required — that is, no feedback paths from the airplane were required to be closed on the ground. Both proportional and discrete commands required implementation from the ground station. Primary pitch, roll, and yaw commands, as well as the throttle and brakes, were proportional while gear, flaps, engine fuel shutoff, landing gear up/down, nosewheel steering left/right, and emergency brakes were the discrete commands. The ground system was duplex with some simplex elements while the airborne system was simplex or single-string. Figure 4 represents a simplified illustration of the uplink command path and the downlink telemetry signals.

The rationale for using the single-string airborne system was that a flight crew would be aboard during RPV testing and that they would assume command in the event of any RPV anomalies and that once checked out the unmanned mission would be relatively short in duration, thereby minimizing exposure time. Providing redundancy in the RPV systems aboard the B-720 aircraft was considered beyond the scope of the program because of time and monetary constraints.

Ground Systems

Flight test instrumentation data were transmitted to the ground as a pulse coded modulation (PCM) data stream at 200 Hz.[1] The ground station received and decommutated the data into usable data words in counts. The ground systems were divided into active and standby (or A and B, respectively) systems. The simplex elements in this system included the pilot's control stick computer, the relay box, and the SIBLINC (the hardware interface between computer and cockpit).

Cockpit instrument displays included two forward-looking TV receivers (one color and one black-and-white), attitude direction indicator (ADI), radar altimeter, airspeed, altitude rate, engine RPM, fuel flow, EGT, and engine pressure ratio indicators.

The ground pilot's controls consisted of conventional stick and rudder pedals for three-axis proportional control of the aircraft. Stick and rudder characteristics, such as breakout force, force gradient, limits, and trim rates, were selected by the project pilot to obtain desirable handling qualities. A proportional throttle was also provided which was physically similar to the four throttle controls aboard the B-720, however, only a single throttle command was transmitted to the aircraft, as the onboard throttle handles had been linked together to move as one unit.

The control law computers contained the ground-to-air control law, as well as guidance algorithms. The code in both computers was identical. The pilot's stick and rudder pedal commands were output from the stick computer to the active control law computer. These commands were also passed to the SIBLINC and transferred to the standby control law computer. Most of the discrete commands were passed through the SIBLINC to both the active and standby computers as were the active proportional throttle and brake commands. Switching from active to standby systems was automatic only if the active control law computer failed, otherwise fault detection and switching was done by the pilot.

Airborne Systems

The uplink receiving and decoding system consisted of dual antennas, dual receivers, a signal combiner, and an uplink decoder. The signal combiner continuously combined the output signals of the dual receivers such that, regardless of the orientation of the aircraft with respect to the transmitting antenna, the best signal was available for all uplink commands.

The interface box provided the signal interface between the uplinked signals and the airplane systems. These signals were received as digital signals and output as analog signals for the proportional commands and as relay driver signals for the discrete commands. For flight crew safety during manned flight tests, the command signals to the emergency brakes and engine kill functions were physically disconnected. Each of the other functions could be disengaged by the autopilot disengage switch action by either the B-720 pilot or copilot. The autopilot disengage switches were located on the pilot's and copilot's control wheels.

The variable mode Bendix PB-20D autopilot was modified to receive the uplink pitch, roll, and

yaw ground commands. The glideslope/auto mode was designed so that ILS analog radio commands were the input commands to the elevator (glideslope) and aileron (localizer). This mode was, therefore, selected to receive the uplinked pitch and roll commands with a rudder command added to complete the three-axis control.

A variety of other modifications to the autopilot were required for the CID program. These included the bypassing of all automatic disengage functions due to either fault detection or erroneous engage procedures. However, for the manned RPV test flights the three-phase power monitor and pilot/copilot emergency autopilot disengage functions were retained. Unused or deactivated electronic components were physically removed in an attempt to simplify the autopilot and eliminate as many potential failure points as possible.

The B-720 aircraft had an existing speed command of attitude and thrust (SCAT) system with a limited authority throttle servomotor which was connected by clutches to all four throttles. This system was modified to receive the single uplinked proportional throttle command.

An independent terminate system was installed aboard the B-720 aircraft, to ensure that the aircraft would not pose a threat to populated areas in the event of any RPV control system failure. This system was designed to be isolated, as much as possible, from the onboard B-720 flight control systems. Activation of the termination system resulted in the following actions aboard the aircraft.

1. Engine 1, 3, and 4 fuel valves were commanded to the off position immediately. To retain aircraft electric and hydraulic power, the number 2 engine was programmed to shut down 25 sec later.

2. Emergency pneumatic brakes were activated.

3. Landing gear was lowered.

4. Throttles were moved to the idle position.

5. Stabilizer was commanded to the maximum leading edge up (nose down) position.

6. Rudder was commanded to full nose right.

Once the terminate command was issued, it was irreversible. The terminate system was demonstrated during ground tests, but was never active during manned flights. During manned flights, the system was wired to a test box where a series of lights which, when lit, gave a positive indication that the system operated as specified.

CONTROL SYSTEMS

The following control systems are represented as continuous systems using the Laplace transform variable s representation. All systems were mechanized in a ground-based digital computer for analysis with all appropriate sampled data transformations being made. The mechanization of the

Bendix autopilot, shown in the Figs. 5 to 8, represents a simplified version as it was used in the CID program and mechanized in the simulation. All of the block diagrams in Figs. 5 to 8 represent the systems in their final configuration.

Pitch Control System

The control laws for the pitch axis are shown in Fig. 5. The RPV pilot commands pitch angle of the B-720 airplane by movement of a control stick in the ground-based cockpit. A pitch attitude command that was proportional to stick deflection was sent to the pitch axis of the PB-20D autopilot. Full stick deflection of ±10.16 cm (±4 in.) commanded -12° to +15° of pitch angle. A pitch trim button was located on the RPV pilot's stick that moved the stick at a constant rate of 2.9° of pitch attitude per second.

Figure 5 also shows how the autopilot processed the uplink attitude command. The signal was summed with pitch angle and pitch rate feedbacks, and with a turn compensation term. The autopilot generated a command to the autopilot servo, which in turn deflected the control surface through a tab-elevator system. An autotrim command was also generated which drove the stabilizer to reduce the elevator servo loads.

The autopilot servo model used on the simulator is shown in Fig. 6. This model was developed from a comparison of simulation and flight step responses (see Manned Test Flights section).

Roll Control System

The ground-based and onboard autopilot control laws for the roll axis are shown in Fig. 7. The RPV pilot commanded roll attitude of the aircraft proportional to the lateral displacement of the control stick in the ground-based cockpit. The pilot inputs went through a small deadband and generated commands which were uplinked to the roll axis of the onboard autopilot. Full deflection of the roll stick (±10.16 cm (±4 in.)) commanded ±35° of bank angle.

Yaw Control System

The RPV pilot commanded rudder to the B-720 aircraft through the yaw damper. The RPV rudder control system is shown in Fig. 8. The rudder pedal position signal was passed through a deadband, and a rudder command proportional to pedal deflection was uplinked to the airplane. Full rudder pedal commanded ±25° of rudder deflection.

Nosewheel Steering System

A diagram representing the implementation of the ground-based cockpit's nosewheel steering system is also shown in Fig. 8. The RPV pilot generated a nosewheel position command that was proportional to rudder pedal displacement when the nosewheel steering was engaged. This command was then compared to the downlinked nosewheel servo-position command. A nose-left or nose-right discrete command was uplinked to the onboard RPV nosewheel steering system motor. This motor then

drove the nosewheel servo command. A deadband in
the pilot command was used to reduce the magnitude
of the limit cycle. This limit cycle resulted
from the delay in the feedback through the down-
link system. The amount of deadband necessary was
determined from actual system use (see Manned Test
Flights section).

Throttle and Autothrottle Systems

The RPV pilot commanded the throttle to the
airplane through a single lever in the RPV cock-
pit. An autothrottle was provided in the ground-
based software to free the RPV pilot from making
throttle adjustments during flight. Figure 9
shows the mechanization of the ground cockpit
throttle system, the autothrottle implementation,
and the simulation model of the engine dynamics.
The throttle was limited to a range between
68-percent engine rpm (idle) and maximum throttle.

The autothrottle was engaged to hold indicated
airspeed at a prespecified value. A reference
airspeed of 146 knots was selected to obtain the
desired true airspeed of 152.5 knots at impact,
after passing through ground effect. The airspeed
that the autothrottle controlled was the down-
linked, onboard-computed airspeed (V_{cas}). This
downlinked airspeed was compared to the reference
airspeed to generate an airspeed error. This
error signal was passed through a proportional and
an integral path. The integrator was initialized
at the current value of the pilot throttle lever
position and was limited to a -50 percent to
+75 percent range to prevent saturation if the
autothrottle was engaged at an airspeed that was
significantly different than the reference speed.
A filtered, pitch-angle term was used to lead the
throttles when the flightpath was changed. The
autothrottle command was limited to a range of
0 percent to 75 percent (approximately maximum
continuous thrust). This command was uplinked to
the B-720 throttle system.

Brake System

The ground cockpit had toe brakes incorporated
in the rudder-pedal system. The RPV pilot could
command 0 to 100 percent left or right brake by
deflecting the appropriate brake pedal. The pro-
portional brake commands were then uplinked to the
onboard brake system.

GUIDANCE SYSTEMS

General Guidance Configuration

Two modes of guidance information were pro-
vided to aid the RPV pilot in flying the B-720
aircraft. One mode, the racetrack guidance,
assisted the pilot in flying the racetrack pat-
tern. The second mode, final approach guidance,
assisted the RPV pilot in flying the desired
approach path and aided in attaining the desired
conditions at impact. The racetrack and final
approach patterns can be seen in Fig. 3.

Racetrack and final approach guidance was pro-
vided for the crash runway and runway 25. Run-
way 25 is a lakebed runway that would be used to
land and recover the B-720 in the event of an
abort. There were three guidance options available·

1. racetrack, in which only the racetrack
   guidance was used,

2. final, where only the final approach was
   used, and

3. automatic, in which the racetrack and final
   approach modes were selected automatic-
   ally depending on the location of
   aircraft.

Selection of guidance mode and runway were
made on the RPV CSMC (computer select mode
control) panel.

The reference point for all guidance calcula-
tions was marked by a stake at the impact point on
the lakebed and the coordinates determined using
the NASA FPS-16 tracking radar.

The racetrack guidance system provided lateral
guidance to the RPV pilot in the form of a "fly-
to" flight director needle. Raw position infor-
mation in the form of crossrange position relative
to the racetrack was also presented to the ground
pilot on the localizer bug in the RPV cockpit.
The guidance led the pilot to the racetrack, and
gave appropriate commands to keep him on the
racetrack pattern. Full scale was ±122 m (400 ft)
of crossrange error in the racetrack mode.

The lateral final approach guidance provided
instructions to the RPV pilot using fly-to flight
director needles and raw displacement from the
centerline information. Again, the guidance com-
mand was displayed on the lateral flight director
needle and the raw centerline error was displayed
on the localizer bug of the ground cockpit. Full
scale on the raw data varied linearly from 122 m
(400 ft) of error above an altitude of 518 m
(1700 ft) to 18.3 m (60 ft) at and below 152 m
(500 ft).

The longitudinal guidance provided flight
director and raw displacement information for both
the racetrack and the final approach modes. The
raw information was altitude above or below the
reference altitude, which is the altitude on the
desired glideslope. This error was displayed on
the glideslope error bug in the RPV cockpit. Full
scale varied linearly from ±61.0 m (±200 ft) at
610 m (2000 ft) AGL, to ±15.2 m (±50 ft) at 305 m
(1000 ft) AGL.

As a backup or supplement to the electronic
pitch guidance during final approach, a simple
mechanical system was set up near the impact site
to indicate whether the B-720 was on glideslope
and centerline. A washer with a diameter of
6.4 cm (2.5 in.) was suspended from a frame

located 30.5 m from a television camera. Once properly aligned, the camera-to-washer lineup makes a 3.8° angle with the ground, with the camera looking up the glideslope of the oncoming airplane. When the airplane was on the proper 3.8° glideslope and on centerline, the TV picture would show it directly behind the washer. The vertical lines that held the washer to the frame were used to tell if the B-720 was on centerline. This TV view could be used to make corrections to get back on glideslope or centerline. A TV monitor was available to display this "washer guidance" information to the RPV pilot, next to his out-the-nose camera view.

MANNED TEST FLIGHTS

Manned flight tests of the B-720 provided the means by which available theoretical mathematical models, RPV support software, and RPV hardware were verified for the CID mission. In addition, the aerodynamic effects of the vehicle in close proximity to the ground were determined. Major benefits of the manned flight tests were the assessment of RPV handling qualities and numerous practice CID approaches and practice emergency landings.

Early in the program it was realized that, in order to accomplish the CID mission, a high-fidelity simulation would be required as a mission trainer and to assist in systems development. Mathematical models of the aircraft aerodynamics, autopilot, flight control system, and engines were available. However, certain system gains and dynamic elements were poorly defined or not defined at all. The early flight tests were, therefore, necessary to acquire data with which to improve the data base and provide for further systems development.

For the acquisition of flight data, step input commands were mechanized in the ground-based computer. These step inputs were controlled in both amplitude and time duration, and were input to the elevator, ailerons, and rudder. These step commands were uplinked to the airborne autopilot in place of the normal, ground-pilot control commands. The aircraft responses to the pulses were downlinked and recorded in the ground station for postflight analysis. The flight responses were then compared to pulse response data obtained from the simulation, and modifications to simulator gains and dynamic elements were made until the simulation results matched the flight response.

From the flight test results, it was determined that the yaw-step response matched that of the simulation very well. The pitch and roll responses, however, did not match the simulator results. The flight results indicated that the autopilot pitch gain and the equivalent elevator servo dynamics, as modeled, were in error. The pitch gain problem was traced to an incorrectly grounded autopilot isolation amplifier. After this amplifier was properly grounded, the pitch gain matched that of

the simulation. To fully match the flight response, the simulation elevator servo model dynamics were modified from a first-order model to that shown in Fig. 6. The torque limit in the model of the autopilot servo provided a rate limit, and, in conjunction with the torque feedback from the tab position, provided a position limit that was a function of airspeed. The servo model torque limit was determined from a match of flight test data so that the elevator response was limited to the flight value by the predicted torque required. A time delay was added to the servo model to produce the overall stability of the closed-loop autopilot/servo/elevator system as seen from the flight data. Modifications to the simulator resulted in closer correlations between data from actual flight and those of the simulator.

The roll response showed that the onboard gain was higher than anticipated and saturated the system. The autopilot gain was lowered, a good match was obtained, and the lateral handling qualities were improved.

To determine the dynamic response of the engines, the autothrottle was engaged at an airspeed different than the reference airspeed. This resulted in a step input to the system. It was determined that the engines responded faster than the initial simulation model. The faster responding engines were equivalent to having higher gains in the autothrottle which resulted in oscillatory behavior during flight. Figure 10 shows an engine's fuel-flow response to the step autothrottle maneuver for the original model used in the simulation. The figure also shows the actual response seen during flight 1, the simulator response after modification of the engine model, and the simulator response after modification of the autothrottle control laws. The autothrottle performed exceptionally well in flight after the ground control laws were modified to correspond to the flight test results.

The guidance systems that were designed to aid the RPV pilot during the final mission were also evaluated during the test flights. Some gains in these systems were varied as a result of flight experience, including the scaling gains that scaled the guidance information on the RPV pilot displays. The position of the racetrack was also changed during the flight test period to the position shown in Fig. 3. This change increased the time available for the RPV pilot to line up on track during the final approach.

RPV taxiing of the B-720 for manned test flights allowed observation of the RPV nosewheel steering system performance. Limit cycle oscillations of the nosewheel were observed. The system was designed with command deadbands incorporated to reduce these limit cycles. Once the limit cycles were seen during taxi, the values of the deadbands in the ground software were changed to reduce the oscillations.

Flight test also allowed testing of a new uplink/downlink system, and testing of the onboard autopilot hardware. During the 14 manned test flights, four problems were encountered within the RPV uplink system, interfaces, and autopilot. These four anomalies occured on four different flights. In all cases, the instrumentation available was insufficient to determine the exact cause.

These four anomalies can be briefly stated as follows

1. intermittent loss of RPV uplink signal for approximately 60 sec,

2. apparent loss of pitch-autopilot-command inputs from 28 to 41 sec (two intervals of time);

3. failure of uplink decoder to pass uplink commands for an extended interval following a flight, with the B-720 on the ground,

4. uncommanded 9° left roll in the RPV mode while making a landing approach.

The first three anomalies called for modifications which were implemented based on suspected causes. In each case, the anomaly never recurred. The fourth was traced to the autopilot, but could not be duplicated and the problem never recurred.

The corrective action for the intermittent loss of RPV uplink signal was to relocate the downlink monitor to the second channel on the signal combiner. The corrective action taken for the second listed anomaly was the replacement and interchanging of certain autopilot components. An uplink card replacement was the action taken to correct the third anomaly.

Observing these problems during the manned test flights allowed corrective actions to be made prior to the unmanned impact flight. These anomalies could have compromised achievement of the CID program impact goals had they occurred at the wrong time on the final flight.

Early simulation results indicated that the impact point, sink rate, and vehicle pitch attitude were highly dependent on the ground effect model with specific autopilot gains. To ensure that the specified impact conditions would be met, a series of flight tests were conducted to verify the B-720 ground effects. The B-720 had a positive lift increment and nose-down pitching moment caused by ground effect. With no control system, the airplane would pitch down, losing more lift because of the reduction of angle of attack than the increase gained in ground effect, and would impact short of the target. With a high autopilot pitch gain, the airplane would maintain attitude and impact beyond the target. It was, therefore, necessary to verify the aircraft's ground effects and adjust the autopilot pitch gain. This was to ensure that the lift loss resulting from the

decrease in angle of attack matched the lift increase caused by ground effect. As a result of the flight tests, it was determined that the increment of lift increase caused by ground effects was significantly larger than had been predicted, while the nose-down pitching moment was about as predicted.[2] The result of these tests was a reduction in the autopilot inner-loop gain of 62 percent (see Fig. 5).

All RPV takeoffs and landings were generally satisfactory, although the landings proved to be a difficult piloting task. The difficulty was a result of poor depth perception and lack of peripheral vision through the out-the-nose TV monitor. The poor depth perception was caused, in part, by the use of a standard, low-resolution 525-line monitor.

The flight tests showed the CID mission to be a high-workload task for the RPV pilot. One contributing factor to the high workload was the FPS-16 tracking radar used in the guidance system. This radar lacked the accuracy necessary to be used in a guidance system designed to meet such constrained impact parameters.

The radar accuracy problem can be illustrated by the fact that, prior to flight 11, the radar measured the range to the impact site reference stake as 11,722 m (38,458 ft), and prior to flight 12, the same measurement was found to be 11,715 m (38,435 ft). This discrepancy of 7 m (23 ft) was greater than the allowable lateral error of 4.47 m (15 ft).

Only limited experience with FPS-16 tracking radar driven guidance from previous DFRF programs existed at the beginning of the CID program. The radar-driven guidance appeared adequate at the time.

During the 14 manned test flights, 16 hr and 22 min of RPV control were accumulated, 10 RPV takeoffs were made, 69 RPV-controlled approaches to the CID site with go-around at either 61 m (200 ft) or 45.7 m (150 ft) were flown, and 13 RPV landings on abort runway 25 were performed.

IMPACT FLIGHT RPV RESULTS

The final CID flight was made on December 1, 1984. During the impact flight, some difficulty was experienced in obtaining the desired impact conditions. The following is a review of the events that occurred during the final approach and an evaluation of the significance of these events on the impact conditions that were achieved. The analysis is based on recorded downlink parameters and on the radar and computer generated guidance information.

Impact Conditions

Table 1 summarizes the actual impact conditions compared to the design goals.

The longitudinal and lateral displacement values listed are those of the fuselage impact, rather than the initial left-engine and left-wingtip impact.

Results and Analysis of Impact Flight Approach

Some of the pertinent lateral-directional parameters near impact are shown in Fig. 11 and the longitudinal parameters are shown in Fig. 12. The time histories are broken into four regions (A to D), based on lateral activity, as shown in the figures.

Region A. The lateral activity in region A, which was typical of the entire approach up to this point, consisted of fairly regular pulsing of the stick commanding a left bank. This was required to offset the small bank angle bias of the onboard gyro. This bank angle bias had been a problem on previous flights and resulted from gyro precession during the turn followed by a very slow gyro erection time. The lateral deviation had drifted to about a 9.1 m (30 ft) error at the end of region A. Based on simulator runs, this magnitude of error would be acceptable since it was relatively easy to reduce to the allowable 4.6 m (15 ft) tolerance in a steady-state manner in the time remaining.

Region B. In region B, the RPV pilot stopped making any significant lateral corrections for about 10 sec. This occurred while he was working the longitudinal task since the altitude error was increasing significantly immediately before region B, and was reduced to an acceptable level by the end of the region B. It could have also been caused, in part, from the need to transition between the TV visual display and the cockpit instruments in order to cross check the validity of the guidance information. Whatever the reason, during this time period without any pilot inputs, the roll bias produced a left turn (about a 2° bank). This, in turn, caused the lateral deviation to start moving rapidly to the left (rapidly in terms of the 4.6 m (15 ft) constraint). The actual crossrange drift rate was about 0.9 m/sec (3 ft/sec) at the end of region B.

Region C. In region C, with the longitudinal problem in hand, the pilot became aware of the lateral motion to the left and began correcting with several right bank commands. The drift to the left was stopped and reversed, which resulted in the airplane moving equally rapidly toward the right and stopped with about a 9.1 m (30 ft) error to the right by the end of region C.

Region D. At this point, the go-around decision point of 46 m (150 ft) AGL had been reached. Just prior to this decision point, the airplane was slightly to the right of the centerline and a go-around was considered by the pilot, but it appeared that sufficient altitude remained to maneuver back to the centerline. With this assessment of the situation coupled with the concern about the lack of redundancy in the overall system, the decision was made to continue the

approach. At about 30.5 m (100 ft), a fairly sharp, left lateral command was initiated to correct the lateral offset error accompanied by a pushover to ensure that the airplane did not overshoot the target area. The left lateral command initiated a lateral oscillation which did not have time to damp prior to impact. Depth perception through the TV was poor and it was difficult to accurately judge where touchdown would occur. The aggresive, lateral piloting technique used in region D did arrest the diverging lateral error. However, this did not occur within the desired range and generated relatively large bank angles which resulted in a significant bank angle at impact.

In the pitch axis, the pitch angle was held within the desired range (0 to 2°) during this final region, although it was oscillating. The pitch command was oscillatory and diverging. The altitude error was converging on the desired value until the large bank angles occured. At this point, altitude was lost because of slight pushover (about 1°) and the lift loss caused by the banking. This resulted in the impact being short of the desired point.

This portion of the flight profile resulted in a significantly higher pilot workload than the test flight emergency landings. This resulted from the requirement to touch down on a specific point. It was difficult for the RPV pilot to integrate all the information presented and then to manually adjust the flight path to meet all the desired conditions. The controls design team generally agreed that some form of head-up-display should have been used in the CID program and that more of the piloting tasks should have been automated.

This analysis indicates that the desired impact conditions were not met as precisely as desired because of two related factors:

1. a bank angle bias that could produce significant turn rates if unattended; and

2. a high workload task which did not allow continuous monitoring of both the pitch and roll axes. A primary contribution to the workload was the need to integrate information from the cockpit instruments and the TV visual information. The RPV pilot was also saturated with too much information, which contributed to the high workload of the task. He had the out-the-nose TV visual information and the "washer guidance" TV to monitor, as well as the instrument panel guidance information. None of these sources alone provided consistent, accurate guidance information, so the RPV pilot had to integrate all three pieces of information and, at the same time, control the B-720. The pilot also had to visually scan between the monitor and the instrument panel to see all available information.

These factors, when taken together, created a dynamic situation which made it very difficult to realize the impact conditions in as smooth and accurate a manner as was desired.

Although not all impact parameters were within the desired tolerances, most were, and those not within the desired tolerances probably did not adversely affect the experimental results. This brought some realism to the experiment which is representative of an actual crash.

CONCLUDING REMARKS

The remotely controlled impact demonstration program was undertaken to acquire data that would contribute to the technology for the improvement of transport aircraft occupant crash survivability. The Boeing B-720 transport used in this test was modified to be flown remotely from the ground using the onboard Bendix PB-20D autopilot as primary control. Simulation was used to design the remotely controlled systems, which were verified and validated in flight tests. Extensive flight tests were performed to practice the impact scenario. However, no approaches to the impact site below an altitude of 45.7 m (150 ft) were accomplished.

During the flight tests, it was realized that the tracking radar data used in the guidance was not accurate enough for the task. Therefore, relying on the guidance alone was inadequate. Better guidance information could have been obtained by using a microwave landing system (MLS), rather than the tracking radar.

The CID impact piloting task was a higher workload task than the flight test RPV landings because of the tight impact constraints. The final mission proved to be a particularly high workload task because of the requirement to integrate all of the information presented to the pilot. During the early test flights, the controls design team generally agreed that some form of head-up display (HUD) should have been used and that more of the piloting tasks should have been automated. These features could improve the guidance only if better information were incorporated into the guidance system, such as from the aforementioned MLS.

As a result of the high workload task, not all of the impact parameters were met. However, from a remotely piloted aspect, all ground and airborne systems performed as specified.

Although not all impact conditions were met, all RPV systems performed as specified and, from a remotely piloted vehicle standpoint, the program is considered a success.

REFERENCES

[1]Harney, P.F., Craft, J.B., Jr., and Johnson, R.G., "Remote Control of an Impact Demonstration Vehicle," NASA TM-85925, Apr. 1985.

[2]Curry, R.E., and Bowers, A.H., "Ground-Effect Analysis of a Jet Transport Airplane," NASA TM-85920, Jan. 1985.

Table 1 Design goals and impact conditions

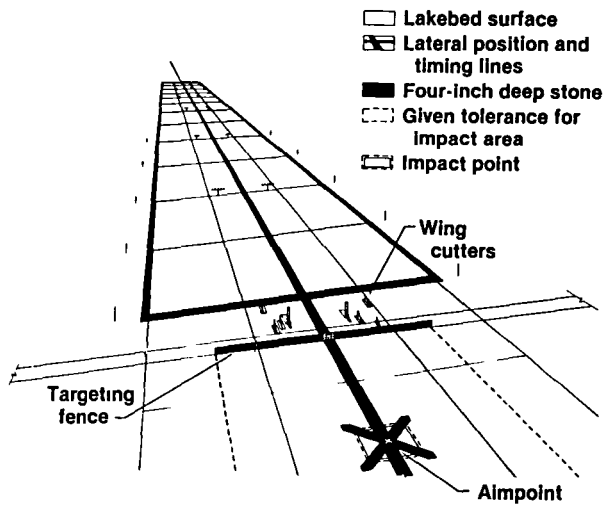|	Design goals	Impact
Velocity (groundspeed), knots	152.5 ± 2.5	151.5
Rate of sink, m/sec (ft/sec)	5.18 ± 0.30 (17 ± 1)	5.3 (17.4)
Pitch angle, deg	1 ± 1	-0.25
Bank angle, deg	0 ± 2	-12
Heading (relative to impact runway heading), deg	0 ± 2	1.5
Lateral displacement (Y), m (ft)	0 ± 4.6 (0 ± 15)	+6.1 (+20) right
Longitudinal displacement (X), m (ft)	0 ± 22.9 (0 ± 75)	-85.7 (-282) short

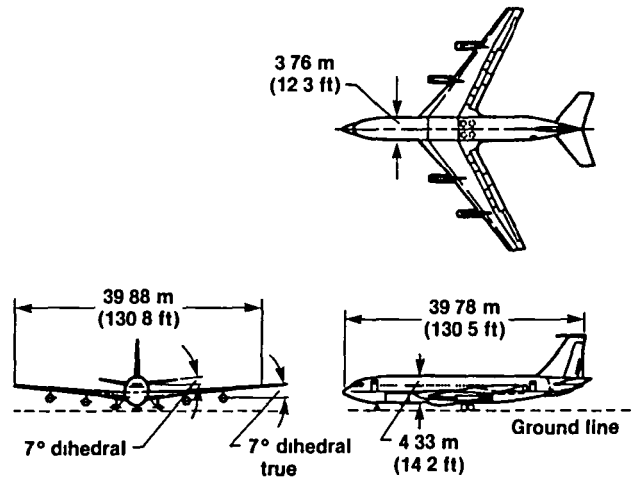Figure 1. *Controlled Impact Demonstration Aircraft Crash Site*

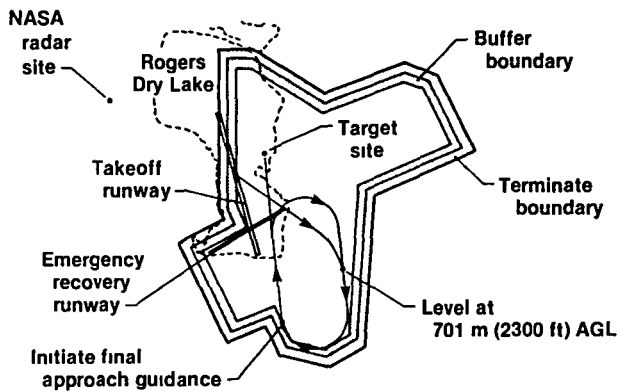Figure 2. *Three-View Drawing of B-720 Airplane*

Figure 3. *Controlled Impact Demonstration Ground Track and Sterile Area Boundary*
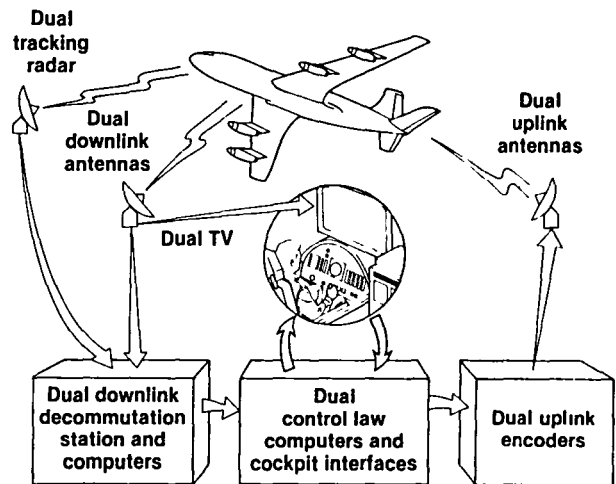

Figure 4. *Controlled Impact Demonstration Ground Remotely Piloted Vehicle Control System*
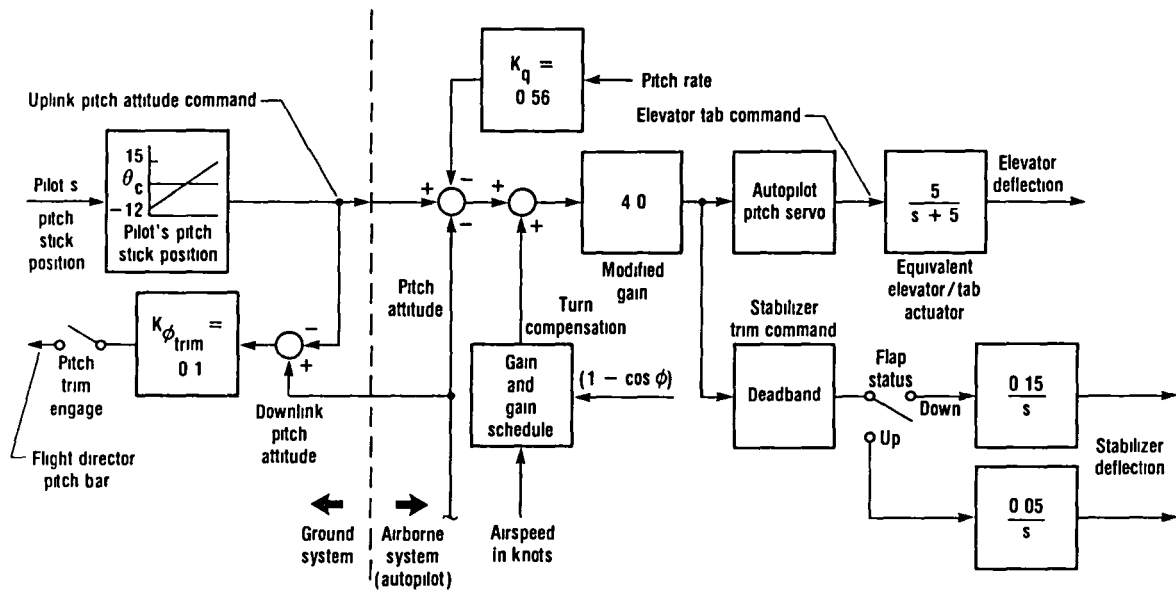
Figure 5. Controlled Impact Demonstration Ground and Airborne Pitch Control System
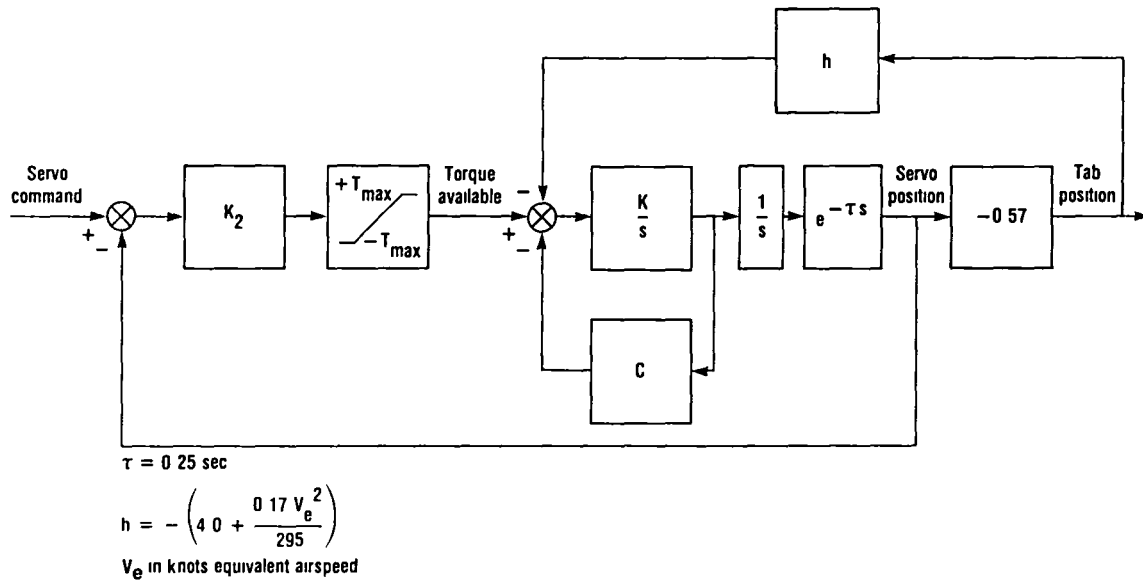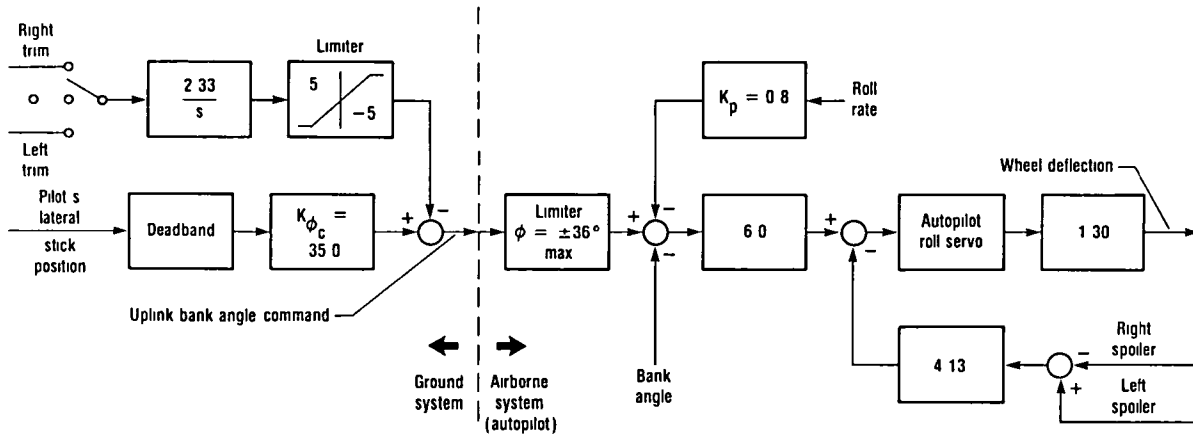

$\tau = 0.25$ sec

$$h = -\left(4.0 + \frac{0.17\,V_e^2}{295}\right)$$

V_e in knots equivalent airspeed

Figure 6. Controlled Impact Demonstration Autopilot Pitch Servo Model

(a) Ground to Wheel Command Path
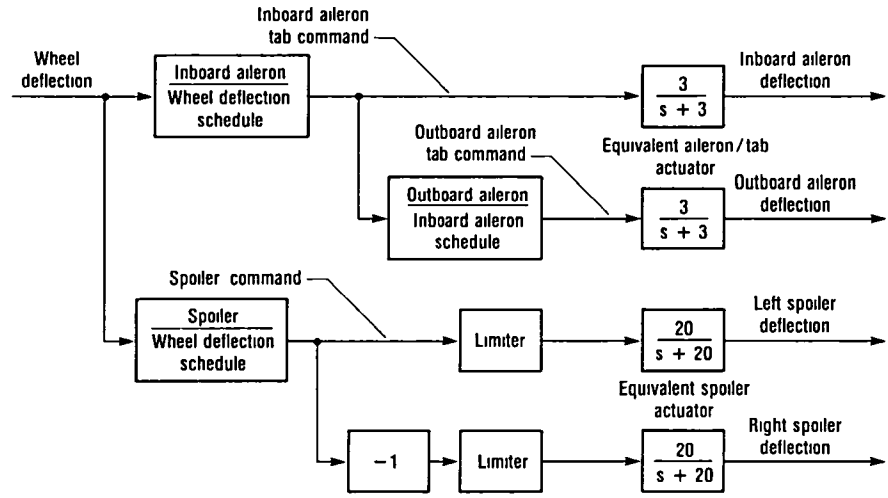
(b) Wheel to Aileron and Spoiler Command Path

Figure 7. Controlled Impact Demonstration Ground and Airborne Roll Control System

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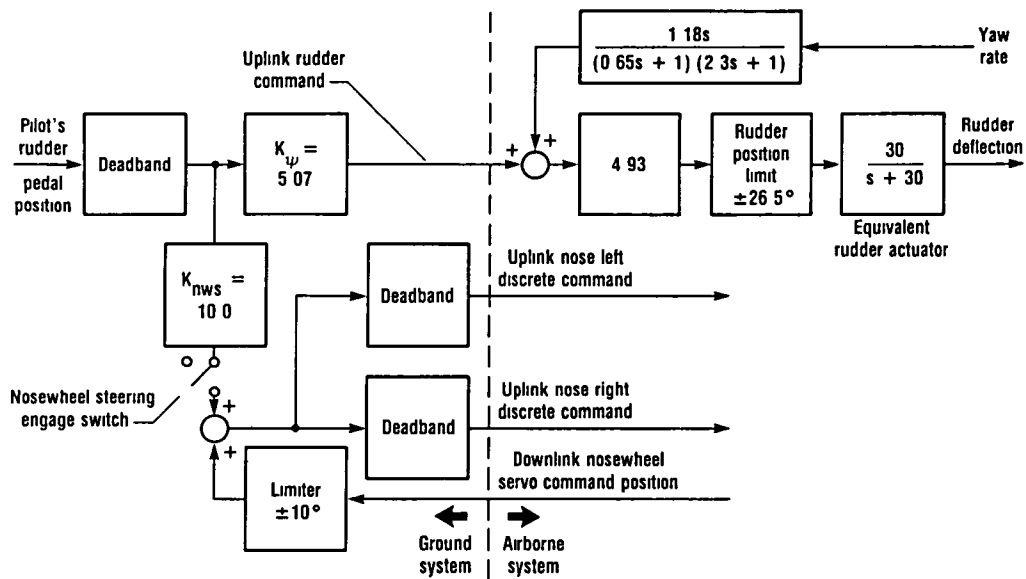
Figure 8. Controlled Impact Demonstration Ground and Airborne Yaw Control System
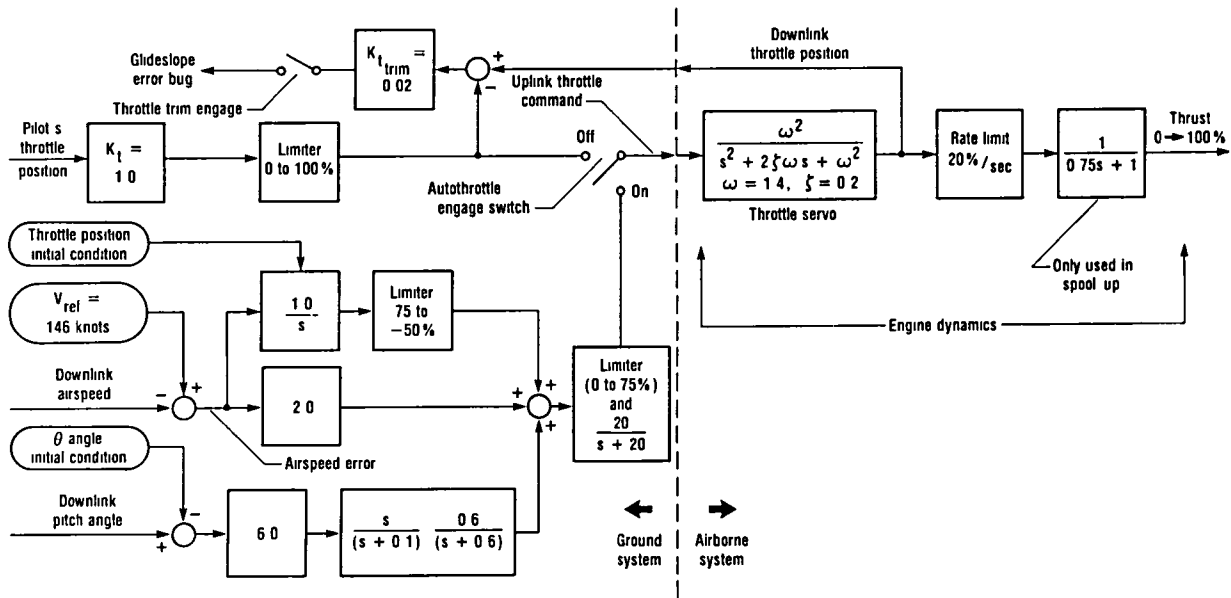
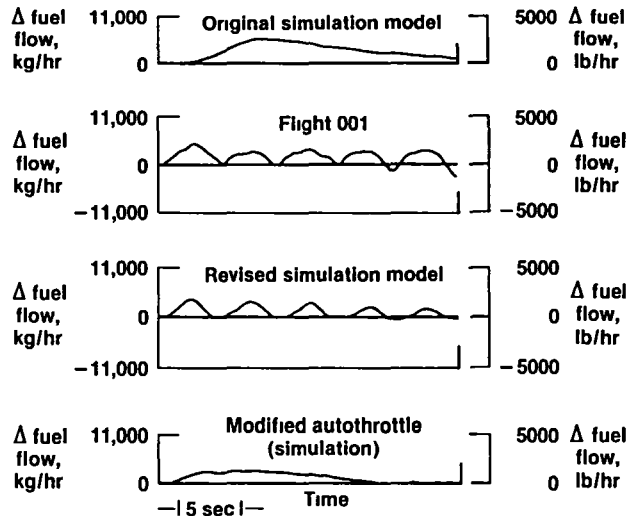*Figure 9. Controlled Impact Demonstration Ground and Airborne Throttle Control System*

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Figure 10. *Comparison of Flight and Simulation Engine Fuel-Flow Response to an Autothrottle Step Input*
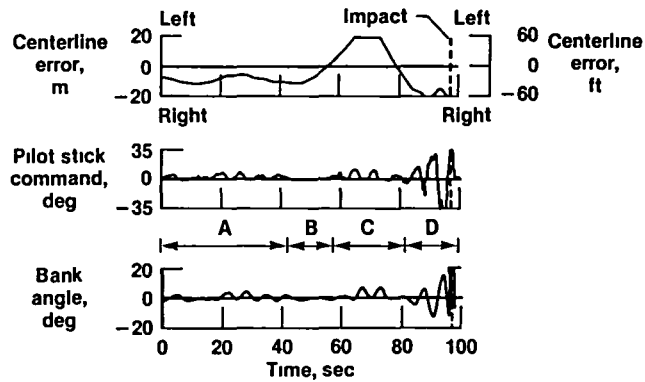

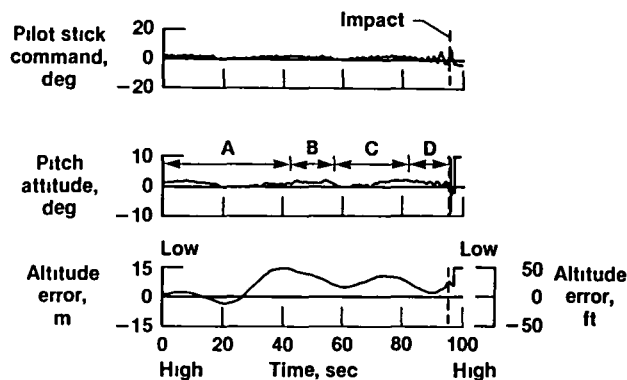*Figure 11.* *Lateral-Directional Time Response From 498 m (1630 ft) AGL to Impact*

Figure 12. *Longitudinal Time Response From 498 m (1630 ft) AGL to Impact*

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16 Abstract

NASA Ames Research Center's Dryden Flight Research Facility and the Federal Aviation Administration conducted the controlled impact demonstration (CID) program using a large, four-engine, remotely piloted transport airplane. Closed-loop primary flight control was performed from a ground-based cockpit and digital computer in conjunction with an up/down telemetry link. Uplink commands were received aboard the airplane and transferred through uplink interface systems to a highly modified Bendix PB-20D autopilot. Both proportional and discrete commands were generated by the ground pilot.

Prior to flight tests, extensive simulation was conducted during the development of ground-based digital control laws. The control laws included primary control, secondary control, and "racetrack" and final approach guidance. Extensive ground checks were performed on all remotely piloted systems. However, manned flight tests were the primary method of verification and validation of control law concepts developed from simulation.

This paper discusses the design, development, and flight testing of control laws and systems required to accomplish the remotely piloted mission.

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