Hybrid Apollo docking simulation

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INTRODUCTION
The Apollo manned lunar landing program of the
National Aeronautics and Space Administration has
as requirements the execution of various rendezvous
and docking maneuvers in space by the command
and service module (CSM), the lunar module (LM), and
the S-IVB space vehicles. To insure the success of
the mission, the following four docking maneuvers are
required.

1. Earth' orbital
2. Translunar
3. Lunar orbital
4. Lunar separation

These maneuvers involve several different vehicle con­
figurations exhibiting very different dynamic charac­
teristics. The docking hardware assemblies (Figure 1),
designed and fabricated by North American Aviation,
Inc., consist of an active probe mounted on the CSM
and a cone-shaped drogue mounted on the LM. The
docking system hardware was designed to perform two
essential functions:

1. During docking in space, the docking system
attenuates the energy between the two vehicles and,
after achieving a latched configuration, draws the
vehicles together to form a tunnel for the transfer of
personnel and equipment.
2. The docking system allows safe separation of
the two vehicles during lunar orbit.

The purpose of the docking simulation was to flight­
qualify the probe and drogue hardware prior to
their use during an actual mission. These subsys­
tems had previously been evaluated by all-analytical
simulations and had been subjected to three-degree-of­
freedom, all-physical simulations using air-bearing
vehicles. However, because of the critical importance
of the four docking maneuvers to a successful lunar
landing mission, NASA decided to conduct full six­
dergree-of-freedom tests on actual flight hardware under
a simulated space environment. The following are the
objectives of this test program:

1. To demonstrate the structural capability of the
docking system and its ability to attenuate the energy
of the closing vehicles.
2. To demonstrate the latching capability of the
system under a variety of conditions.

A detailed evaluation of the control aspects of the
docking maneuvers was not included in this study.

Problem characteristics
The Apollo docking maneuvers resemble very-light­
ly-damped oscillators. The rigid-body natural fre­
frequencies are 2 to 3 cps with frequencies of interest
ranging up to 10 cps. Reaction-control-system (RCS)
frequencies range up to 80 cps. The assumption was
made that the target vehicle RCS had no initial error,
which then allowed the docking maneuvers to be
simulated with six relative degrees of freedom. Only
five axes were dynamically significant but, the sixth
axis (roll) was included primarily for the purpose
of simulating initial roll angles.

For this test program, simulation tolerances of
±0.040 inches radially were specified at the latching
rings. For one docking configuration (transposition)
the distances from the vehicles center of gravity to the
docking mechanism are 375 and 165 inches respectively.
In that case, a radial tolerance of ±0.040 inches
is 0.007% of full scale. Figure 2 is a graphic repre­
sentation of the vehicles showing this relative accuracy
requirement.
Figure 1—Apollo docking hardware

Figure 2—Relative accuracy requirement

INTERNAL ACCURACY = \frac{0.040 \text{ inch}}{165 \text{ inches} + 375 \text{ inches}} = 0.007\%

COMMAND SIGNAL ACCURACY = \frac{0.040 \text{ inch}}{20 \text{ inches (full scale)}} = 0.2\%
Simulator concept

Since the masses of the vehicles are large compared to those of the docking system components, it was necessary to simulate the rigid-body dynamics. To achieve realistic motion, it was necessary to include a simplified functional simulation of the control systems. Furthermore, elastic-body bending and fuel slosh have frequencies within the range of interest. To test the docking system, NASA devised the Apollo Docking Test Device (ADTD) concept (Figure 3). The probe and drogue hardware are mounted on the docking rings, and each ring is supported by six load cells. The load cells are mounted on two structures which can be moved hydraulically. The probe side of the ADTD has two degrees of freedom (X-axis and roll axis). The remaining four degrees of freedom are on the drogue side of the ADTD. Using loads measured by the ADTD, a computer simulated the vehicle dynamics and fed position commands back to the hydraulic actuators.

The ADTD was built by American Machine and Foundry Company. It weighs 50 tons, largely because of the seismic-mass base plate. The six main hydraulic actuators of the ADTD are controlled by position servo-mechanisms and have a frequency response of 12 cps. Riding "piggy back" inside the main translational actuators are high-frequency, low-amplitude actuators for the simulation of elastic effects. The ADTD is capable of operation in a 10^4-ton environment, in temperatures of -80° to 250° F.

In addition to the hydraulic and load-cell systems, the ADTD incorporates quick shutdown or abort logic for the protection of the personnel and of the docking system. The abort system has inputs from the computer; from the operator, and from circuits monitoring the motion envelope, the forces, the velocities, and the strains and impulses.

The computer

The computer used for the docking system simulation was an EAI 8900 hybrid system (Figure 4). In explaining why a hybrid computer is used, the engineer is normally placed on the defensive. In this case, the simulation engineers felt that the hybrid computer was the best tool for the job. To justify this position, it is necessary to explain why an all-analog or all-digital computer system could not have been used.

In 1964, when this work was begun, there was no
digital computer available which could do the work in real time. Furthermore, since the docking simulation was to operate on two shifts per day, a large digital computer would have been prohibitively expensive.

An all-analog simulation was given serious consideration. In fact, the docking simulation employed an interim analog computer system, which consisted of three EAI 231 R computers, a DOS 350, and an ADIOS. While the use of the interim analog computer was very beneficial in debugging the mathematical model, in solving computer-hardware interface problems, and in familiarizing personnel with the problem, it nevertheless demonstrated conclusively that an analog computer could not solve the problem satisfactorily.

The most pertinent reason for abandoning the analog simulation was accuracy. As explained earlier, this simulation required small differences of large numbers. The required resolution was outside the range of a single amplifier, not to mention the overall resolution of a 400-amplifier problem.

Of equal importance was the need for (1) fast turnaround, (2) convenient setup, (3) virtually foolproof operation, and (4) extensive documentation. Figure 5 is a summary of the analog procedures necessary for operations and indicates approximate times for each step. Because of the flight-qualification nature of the project, all operator functions were contained in a written procedure or countdown. For the analog simulation, 5 days of leadtime was needed to allow for certain changes which required off-line support of two digital computers. A setup and static check of the analog simulation required a minimum of 3 hours. Changing docking configurations also required 3 hours.

Since these operations were extremely time consuming, they could not be performed very often. There was also considerable uncertainty as to what problem the computer was actually solving, since production-run documentation was virtually nonexistent.

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**Figure 4**—The EAI 8900 hybrid computer system

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**Figure 5**—Summary of analog procedures

Essentially, use of the hybrid computer system removed the operator from the loop. The operator ran the simulation from an interpretive control program. A complete setup and static check was performed in 10 minutes, exclusive of any troubleshooting required but including all operations formerly done off-line by another computer. The results of all operations were documented in a very readable form which reflected the actual state of all problem parameters. Having this capability, static checks were performed with comparative frequency, thus increasing overall confidence in the simulation. Figure 6 is a summary of comparable information and times for the hybrid system. The hybrid system also permitted the incorporation of real-time, on-line diagnostics and debugging aids. For example, this program could supply simulated forces to permit dynamic checking of the problem, without the ADTD, on an open-loop basis. During a test, the
computer continually monitored error conditions such as analog computer overloads, A/D and D/A converter over-ranges, timing failures, and erroneous operator commands. If an abort occurred in the ADTD or in the computer, an analysis of the abort cause was performed, and the offending condition was documented automatically. Figures 7 and 8 are examples of the documentation which was extremely necessary for this simulation.

TOTAL TIME

30 MINUTES

THE OPERATOR IS THEN NOTIFIED OF ANY POTSETTING OR STATIC CHECK ERROR, CONTROL OF THE COMPUTER IS THEN TRANSFERRED TO A REMOTE PANEL AT THE SIMULATOR, DOCUMENTATION OF ALL DATA, TIME HISTORIES, AND OPERATING PROCEDURE PROCEEDS AUTOMATICALLY.

Figure 6—Summary of hybrid procedures

Availability was also a major consideration in using the hybrid computer. The 8900 system was procured primarily for this simulation, but it was also necessary to use a general-purpose computer system which could also solve other types of problems encountered in the Apollo Spacecraft Program.

The simulation

Two mathematical models were used in the simulation. The first was an open-loop algebraic model used only for initialization. It will be discussed later. The second model was a six-degree-of-freedom, rigid-body representation of two vehicles. It received inputs from the load cells and developed forces, moments, and body rates for each vehicle. Relative velocities were then computed and integrated to achieve relative displacements. A final transformation converted the relative displacements to the ADTD coordinate system. The model also included a two-stage reaction control system for each vehicle. Provisions were made for the addition of elastic-body-bending and fuel-slosh models. Figure 9 represents the major blocks of the total mathematical model (Reference 2).

The model was formulated by expanding the equations of motion for each body in its axis system and then describing the relative motion in the axis system of one of the bodies. To eliminate unnecessary calculations, axis systems and rotational sequences were chosen which would exploit the ADTD capabilities. Since the equations were formulated in one body axis system, it was unnecessary to convert the motion of each vehicle to an inertial system, to calculate the relative motion, and then to transform the relative motion into the reference body system. This reduced the number of transformations from 12 to 7 and improved the solution accuracy.

After the decision was made to use a hybrid computer system for the simulation, it was necessary to analyze the problem in detail to determine the best distribution of computation to be programmed for each computer. The following factors were considered:

1. Real-time solution constraints
2. Computation accuracy requirements
3. Economy of equipment
4. Ease of operation
5. Computer-ADTD interfacing
6. Computation frequencies

After imposing the aforementioned considerations, the model was programmed with the force and moment resolutions, the body rate computations, and the RCS implemented on one analog computer and the force abort system implemented on the other analog computer. The digital computer calculated the relative velocities, relative positions, and the actuator command signals.

This particular distribution very naturally satisfied the previously mentioned considerations. The digital computer was capable of handling its function in real time. It updated at 100 frames per second, giving 40 samples per cycle at the natural frequency of the system and 10 samples per cycle at the highest frequency. The relatively higher frequencies of the forces, the moments, and the control system were programmed
Figure 7—Line printer output

$JOB V14 PRODUCTION CONTROL DECK

ENTER NAME.

MORRISON

PUT 8800 UNDER I/U COMPUTER CONTROL FOR MUTES AND ADDRESSES.

PRESS FLAG 8 TO CONTINUE.

RCS = F

CKOUT = T

ENTER OPTION NUMBER AS FOLLOWS, THEN CARRIAGE RETURN

1 = STATIC TEST
2 = CONFIGURATION SETUP
3 = RUN SETUP
4 = INITIALIZATION
5 = IDLE WITH INTERRUPTS ENABLED
6 = TOGGLE RCS
7 = TOGGLE CKOUT

2

SEQUENCE ERROR

LOAD CONFIGURATION DATA

NEXT OPTION PLEASE

3

ARE COEFFICIENTS FOR THIS RUN TO BE COMPUTED OR READ FROM CARDS?

1 = COMPUTE
2 = READ CARDS

1

RUN SET UP COMPLETE.

NEXT OPTION PLEASE

4

INITIALIZED.

RUN TERMINATED BY LIMIT IN SPIT AT T = 14.21 3/05/67 11:13:20

INITIALIZED.

RUN TERMINATED BY LIMIT IN SPIT AT T = 14.21 3/05/67 11:14:13

INITIALIZED.

RUN TERMINATED BY MANUAL OPR ABORT AT T = 1.79 3/05/67 11:15:31

INITIALIZED.

RUN TERMINATED BY FORCE ABORT FX2 AT T = 10.00 3/05/67 11:17:53

Figure 8—Typewriter output
on the analog computer. Figure 10 is a time history of the forces and moments of a representative docking run.

The accuracy problem arose when the relative body motions were transformed to the reference points in the probe and in the drogue. To overcome the problem this computation was programmed on the digital computer.

Figure 9—Simulation block diagram

Figure 10—Time history of forces and moments
The available equipment was employed very economically since a minimum of interfacing equipment was required. Only 12 A/D channels were required for the velocities, and six D/A channels were used for the hardware command signals. Fourteen other D/A converters were used for data acquisition. Furthermore, since all transformations were performed digitally, no resolvers were required, and the number of multipliers was minimized.

Implementation of the dynamic model was 75% of the analog task but only 25% of the digital program.

The following tasks were also integral to the simulation:

1. Setup, checkout, and limited automatic scaling capability—A full static check required about 3 minutes; a complete initial setup or change in docking configuration required 5 minutes. Because of computer requirements on other projects, a goal of 30 minutes notice from cold start to operational readiness was established. This goal was achieved by automating in every possible area.

2. Real-time control logic and dynamic error checking—To prevent damage to the hardware and to prevent unintentionally aborted runs caused by operator errors, sequencing checks were made on all control functions. Control logic permitted local operation at the computer or fully remote operation from the simulator console. Dynamic checks were provided for computer problems such as overrange, overloads, excessive A/D offsets, and interrupt timing errors. Fully automated control of high- and low-speed data-acquisition systems was also included.

3. Development and calculation of flight trajectories.—The open-loop algebraic mathematical model (referred to earlier) was developed only to achieve the specified initial conditions for a particular docking run. The customer for this project (another NASA division) specified the different test cases by assigning miss distances, misalignments, and relative rates at the time of contact of the probe and drogue. Since the customer was only interested in contact and postcontact data, the method used to reach these “initial conditions” (IC) was arbitrary within the acceleration capabilities of the ADTD. The method chosen to achieve these “initial conditions” (IC) was arbitrary within the acceleration capabilities of the ADTD. The method chosen to achieve the specified initial-contact conditions was (1) to always start from the same reference position with all axes at zero (with the exception of the X-axis) and (2) to “fly” the hardware to contact while, at the same time, achieving all the specified contact conditions. The development of a set of equations to fly the ADTD hardware and, simultaneously, to establish the proper contact conditions was based upon complete knowledge of the ADTD performance capability.

To fly the simplest path by analytical means and to satisfy the boundary conditions at time \( t = 0 \) and time \( t = T \), third-order equations in time were necessary. The cubic equations were used to drive the hydraulic actuator until contact. The derivation of the general equation follows. Let \( y(t) \) represent any of the desired actuator positions such that \( y(T) \) and \( y(T) \) are obtainable and are related to the specified terminal conditions given at time \( T \) (where \( T = \) time of contact of probe and drogue when all preassigned conditions are met). A cubic equation in \( t \) can now be represented as

\[
y(t) = a_t t^3 + b_t t^2 + c_t + d_t
\]

but \( y(0) = 0 \) and \( y(0) = 0 \); therefore,

\[
\begin{align*}
y(t) &= a_t t^3 + b_t t^2 \\
y(t) &= 3a_t t + 2b_t
\end{align*}
\]

where \( 0 \leq t \leq T \). At the terminal time \( T \)

\[
y(T) = a_t T^3 + b_t T^2
\]

and

\[
y(T) = 3a_t T^2 + 2b_t T
\]

Simultaneous solution of equations (3) and (4) for \( a_t \) and \( b_t \) yields

\[
a_t = \frac{T y(T) - 2y(T)}{T^3}
\]

and

\[
b_t = \frac{3y(T) - Ty(T)}{T^3}
\]

Equation (2) was represented \( n \) times for \( n \) degrees of freedom.

Because of the initial bias on one axis (\( X = 25 \) inches) at \( t = 0 \), calculation of the coefficients was slightly different for the \( X \) translational terms and must be calculated as follows:

\[
a_t = \frac{T x(T) - 2X(T) - 25}{T^3}
\]

\[
b_t = \frac{3X(T) - 25 - T x(T)}{T^3}
\]

The digital setup program transformed the desired contact conditions into the body 1 reference frame and set the initial conditions on the body 1 integrators. The body 2 initial velocities were always zero. The setup program also computed the coefficients of the
six cubic equations which describe the flight path. An arbitrary flight time of 10 seconds was normally used. For a test run, the digital computer evaluated the six flight equations in real time until hardware contact, at which time the rigid-body mathematical-model computation began.

Smooth switching between the algebraic flight model and the dynamic model was one of the more difficult tasks in the simulation. At the time of contact, several things happened simultaneously. The analog computer switched from "IC" to "Operate," and the control system was activated. The digital integrators were also initialized using past derivatives computed during free flight. If contact occurred at other than 10 seconds because of system tolerances, a first-order discontinuity occurred. This program was further compounded by leads built into the digital program. These problems will be discussed later in the paper.

The following are other incidental, but very important, features of the program.

1. Extensive logic was provided to assist in troubleshooting. The entire program could be operated in a checkout mode.
2. A force abort system monitored the absolute value of four resolved forces and aborted the test when necessary to protect the hardware.
3. Every test run was automatically documented in considerable detail.
4. XZ and YZ displays were developed for the operator.
5. Upon occurrence of an abort, available data were analyzed to determine the probable cause.

Major problem areas

A project of this magnitude naturally generated numerous problems. Some of these problems and their solutions are of general interest. Visitors to the simulation laboratory first notice the unusual environment under which these tests are conducted. The computer and the simulator are housed in different buildings separated by about three city blocks. One-way video and two-way voice communications are used to establish contact between the two sites. Because of the flight-qualification nature of the tests, all procedures were written into a countdown which was controlled by a test director. The communications coming over the loudspeakers gave the tests a science-fiction aura; however, because of (1) the high energies stored in

![Figure 11—Real-time Apollo docking hardware tests system](http://www.computerhistory.org)
the system, (2) the cost of the facilities, and (3) the large number of personnel on the test operations team, this type of coordination was very necessary. Figure 11 is a graphic presentation of the overall system diagram.

Visitors also note the plexiglas covers and seals on the analog patch boards. The digital program decks, listings, and tapes are similarly sealed. This is a quality control requirement. This sort of control was very awkward at first and was a most unnatural environment for the computer programmers, who felt severely handicapped. However, after several months of operation under these conditions the advantages of reliable documentation became apparent. The files now contain a complete record of every change made since October 15, 1966. Confidence in the accuracy of the documentation and the overall simulation is very high.

The development schedule of this simulation was also well documented and is of interest. The actual programming and checkout was accomplished in 2½ months by three men, working 16 hours a day, 7 days a week. The job ended on October 15, 1966, with quality control acceptance of the work. The job might have been completed earlier, except for the multiple handicaps of a new and untried computer with new, untried software being used by personnel who learned to use the machine while programming this simulation.

Approximately 4 months of complete system checkout followed the October 15 acceptance date. The most significant system problem was stability. The system exhibited divergent oscillations for the light-vehicle tests during lunar-orbital docking as the two simulated vehicles neared a fully-docked position. Analysis of this problem revealed that as the probe retracts, its stiffness is greatly increased, which causes the natural frequency to be increased and causes the system lags to approach 90°.

An analysis of the system components revealed 12° of lag in the ADTD servomechanism and 15° of lag caused by the digital computer at the frequency of interest (2.5 cps). Several things were done to eliminate these lags.

1. The ADTD servosystems were tuned to improve performance in the range of interest, at the expense of higher frequencies.
2. The digital integrator was investigated. The original integrator was a simple Euler algorithm. For the investigation it was packaged in a separate program which duplicated the timing of the full simulation. The package operated as a simple integrator with a single gain-one input and one noninverted output. With this circuit, integrators were studied for the simulation which, as previously mentioned, resembled very-light-damped oscillators. The stability of the all-analog loop was first verified to qualify it as a standard. The EAI 8800 oscillator was extremely stable in the range of frequencies studied (0.1 to 20 cps). Next, one analog integrator was replaced with the Eulerian integrator. As expected, the loop was unstable at 1 cps with a step size of 0.01 second. Then a polynomial lead of 1.5Δt was added to the digital routine (References 1, 3, 6, 7, 8, and 9). This is the theoretical, demonstrated value used to correct for a pure digital lag with a zero-order hold on the output. The oscillator stability was improved but was still not acceptable.

The final step was to use a first-order-predictor integrator and a pure time lead of 0.5Δt on the output. With this configuration the loop was very stable up to approximately 9 to 9.5 samples per cycle (11 cps). At the time the integrator was changed, the ADTD was exhibiting a pure time lag of 6°/cycle. To compensate for this an additional 16.66-millisecond lead was added to the equations, which still had undesirable but acceptable oscillations. Figure 12 represents the integrator evaluation circuits used for the study. Figure 13 is a comparison between the two oscillators.

3. The transmission system, as mentioned previously, was operated remotely. The cable run was 3500 feet through utility tunnels carrying major power trunks. The analog information was carried as ±10 V dc, and control information was +28 V dc and 0 V dv.
Grounding and noise rejection were early problems of concern, but the first system tested for control signals worked very well. Relays were used for isolation, and the commons of the relay power supplies were tied together at each end. Results were not as good for the analog signals. Three systems were tried before a final configuration was reached.

The first was a chopper-driven, transformer-coupled system built by AMF. The phase lags and noise produced by the choppers were excessive. The second method used differential amplifiers. Noise levels were still intolerable. Finally, the transmission terminal equipment was completely eliminated. The lines were then driven, with no problems, directly from operational computing amplifiers. Considerable 60-cycle noise was picked up because of ground potential differences. On input, this was removed by subtracting the signal on the line (which was grounded at the simulator end) from all of the other signals. On output, noise is added to the command information before transmission. Figure 14 is a schematic diagram of the common mode rejection circuits (References 10 and 11).

The evolution of setup and checkout philosophy on this project was very enlightening. The first approach used hand-calculated potsettings and static check values stored on punched cards. It was soon evident that the frequency of changes to these decks would create an excessive workload.

A program to calculate potsettings was written, and the flexibility of changing problem parameters was greatly improved. However, the program was so large that changes to it were difficult. A single potsetting change required about 2 hours for recompilation and loading, but this method was used nevertheless because of reliability and speed of calculation. The reliability stemmed from the fact that data could be loaded into the computer once and used for potsettings, digital parameters, and documentation. This eliminated the inherent unreliability of having a person input the same data twice.

The static check philosophy was generalized somewhat by making it interpretive and by causing it to recognize all forms of A/D communication. However, it was still manually prepared, difficult to maintain, and hardware oriented. Memory space was at a premium, largely because of the size and complexity of the setup programs. As the system monitor grew in size, it became necessary to overlay programs. The simulation had two overlays which were automatically swapped when required. Setup and static checkout was in one overlay while initialization and all real-time programs...
were in the other. The data area was common to both overlays.

CONCLUDING REMARKS

If this simulation were to be restarted with present experience, several significant changes would be made. The functions of potsetting calculations and static checkouts would be performed by a problem-oriented interpreter. This would permit rapid modification to the analog program, with corresponding setup program changes. It would also permit a calculated static check for every configuration, rather than the single hypothetical case which was used. Such an interpreter would look very much like the EAI Hytran Operations Interpreter, but three very significant changes would be made. The interpreter would be subordinate to the main control program of the simulation, and it would communicate with the rest of the simulation by means of a symbol table. Without these features, the operator must input the same data twice in different formats. The interpreter would also have the ability to handle multiple analog computers. In addition, a fully automatic scaling program would be written for the analog and conversion system programs.

The overall development schedule for the project would be entirely different. A clear distinction would be drawn between the buildup of the simulator and its use for testing purposes. This distinction might be extended to include the use of different personnel for the two phases. In particular, the simulator would be built and checked out more slowly.

The load-cell system would be modified to insure the impossibility of measuring physically unrealizable forces and moments (that is, not equal and opposite on the two bodies). This could be accomplished by using load cells on only one vehicle; however, some of the simulation realism would be lost. The best method might be to use an overdetermined set, of perhaps nine load cells per vehicle, which would eliminate the noise and bias problems.

Only through the efforts of a large number of people was the success of this simulation possible. It is hoped that some part of the description of the problems, solutions, and experiences will be useful to others who are now involved, or who may become involved, in simulations similar to the one described.

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