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Digital Autopilot For Apollo: A Radical Change

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It is great to be here and reconnected with NASA people. Just getting ready brought me back to the exciting days of Apollo, and to how much technology has changed.

> Dress codes have also changed. I'm in the NASA engineer's uniform of the Apollo days.

When Richard Katz asked if I wanted to say a few words for the conference, my immediate reaction was "I'm the wrong person to talk about computer designs." Then, I asked if the untold story of how Apollo switched in mid-stream from analog to digital flight control might be of any interest?

Now, computers are everywhere and digital flight control is the norm. It wasn't always so. When Apollo started, the mean time to failure for airplane inertial navigators was around 15 hours, for the good ones, and digital computers in airplanes were not to be trusted. Even fly-by-wire was viewed with suspicion. Any suggestion that something as critical to pilots as flight control could be trusted to a digital computer would have received more ridicule than the early Lunar Orbit Rendezvous ideas.

Even in 1970, there were forceful arguments that digital flight control would not work for the Space Shuttle. This argument was only finally put to rest when some "preflown"[1] Apollo G&N hardware ran the autopilot for the NASA F-8 digital fly-by-wire Shuttle demonstrator.

This is not a talk about technical details. The history of the design is best told by the others who did all the hard and inspired work to make it a reality.

Today is my insider's tale of how, and why, Apollo management took the plunge to change to a digital flight control system in midstream, and did so despite the sincere

[1] The inertial platform, computer and other electronics used were recovered from one of the Apollo flights.

belief of most of the experts at the time that a digital autopilot for Apollo couldn't be done and wouldn't work.

Looking back, the essential ingredients for the change were:

- Intractable Command Module problems – weight and reliability.
- An outsider's view.
- A talented technical team available.
- Serendipity.
- Leaders technically secure enough in their own skins to withstand the "expert community" saying it couldn't be done.

Much of the story is from memory where I was personally involved. I don't think I've included any revisionist history, but 40+ years is a long time ago.

Understanding the tale requires some chronological history of the early Apollo flight control environment.

1961

Step back 43 years to 1961. The MIT Instrumentation Laboratory (MIT/IL) people committed to design and build the primary on-board guidance and navigation (G&N) system for Apollo.[2] The Laboratory's approach is to adapt their latest Polaris inertial guidance package, develop a more capable computer and add optics for space navigation. Industry will build the hardware and NASA and the Instrumentation Laboratory will deliver the G&N systems to the spacecraft contractor.[3]

1962

Move up a year to 1962. North American Aviation (NAA) is selected for the Command and Service Modules. North American's design uses the MIT/IL G&N to feed a conventional analog control system, with an emergency backup strapdown attitude

[2] This was the first Apollo contract because guidance and navigation was considered the longest lead time item for the spacecraft.

[3] This is just a bare outline. Industry built the flight hardware and provided engineering support to the design, development and spaceflights for the hardware and software.

reference.[4] Honeywell is the subcontractor for this system. NAA's design also includes an Autonetics reentry monitoring display to attempt a manually controlled reentry after a failure of the MIT/IL primary G&N system.

With a mission design time of 14 days, the approach to keeping all the electronics functional is to use common modules, as much as possible, carry spares and teach the astronauts to replace what fails.

You may laugh now, but then, in-flight maintenance seemed the best course.

> I still remember a trip to MIT in December of 1962 with the original seven astronauts, and their reaction "you've got to be kidding" to the training outlined for in-flight maintenance of just the G&N system.

1962 ends with the Cuban Missile Crisis, and Houston within missile range.

1963

By June, electrical failures during a Mercury flight provide the hard lesson that the electrical systems must be sealed against water.[5] In-flight maintenance is out and designing enough redundancy into the electronics for 14 day missions is in.

Grumman is selected for the Lunar Module (LM). Their design, like that for the Command Module, uses the MIT/IL G&N as the primary LM system. Grumman includes an abort-only strapdown[6] inertial guidance system, with both the primary and abort guidance systems working through a redundant Grumman designed conventional analog control system.

> As you can imagine, working out the interfaces – hardware and software – to use the same government furnished primary G&N system with two different prime

[4] This strapdown reference was three (3) single degree of freedom gyroscopes aligned with the spacecraft structure.

[5] The liquid cooled cold plates used to cool the electronics condensed moisture from the astronaut's breathing. The Apollo 13 movie scene of when re-entry started, with water droplets coming out of the instrument panels, is what the equipment needed to be protected against.

[6] A strapdown inertial guidance system is one where the gyroscopes and accelerometers are fastened (strapped down) to the frame of the vehicle. In a gimbaled inertial reference system, the orientation of the gyroscopes and accelerometers with reference to inertial space is isolated from vehicle motion through the gimbal structure and servos. In a strapdown system, a fast computer integrates the angular rates of the vehicle to provide virtual isolation of the accelerometers from vehicle rotations.

> spacecraft contractors was not always a conflict-free process. Then, to make life even more interesting, the MIT/IL G&N also needed to interface with the Saturn Instrument Unit to provide backup launch guidance.

The decision is made that early Saturn flights will use existing Block I electronics, after being repackaged to seal against moisture. Going to the moon will be with Block II designs.

There are spirited arguments about the accuracy of navigation based on the Manned Space Flight Network (MSFN). The MIT/IL people (and particularly Milt Trageser) are adamant that it is essential to do navigation from the spacecraft, that radar is not accurate enough and that the spacecraft needs to be self contained in the event the ground based radars are jammed, or otherwise inoperative.[7] The NASA MSFN people argue that the then new atomic clock stability makes it possible to navigate accurately from the ground.

Without experimental flight data, the discussions are sometimes heated. One agreement is that the MSFN will take care of backup navigation in the event something happens to the on-board optics or computers.

Late in 1963, a new Apollo Spacecraft management team comes to Houston. They will play a key role in the decision to change to digital flight control as the primary systems. Joe Shea[8] moves to the Manned Spacecraft Center from NASA Hq. to take over the Apollo Program Office. Joe brings Cliff Duncan[9] from DARPA[10] to lead the guidance and control developments.

The year ends with everyone affected by the President Kennedy's murder in Dallas.

1964

Early in 1964, Cliff Duncan hosts a round robin review of the Command Module Block II Guidance, Navigation and Control (GN&C) overall system design. Among others, Ed White is there for the astronauts, Col. Robert Duffy brings Air Force experience and I am

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[7] In 1963, the Cold Was is alive and there are real concerns about interference from the other side during a flight to the moon.

[8] Dr. Joseph F. Shea.

[9] Dr. Robert C. Duncan.

[10] The Defense Advanced Research Projects Agency.

included as the junior engineer from astronaut support. In Minneapolis, Honeywell presents the options they are considering for reliability and fault tolerance. In this meeting, it is apparent they do not have solutions that fit within the space, weight, performance, schedule and reliability constraints.

At this point, the Command Module Block II GN&C design includes:

- Optics – a telescope for inertial system alinement and a sextant for navigation.
- A gimbaled inertial platform (3 gyroscopes and 3 accelerometers).
- Dual primary guidance and navigation computers (there are two because MIT/IL wants to be sure to have an on-board navigation capability after a computer failure).
- Redundancy in the stabilization and control system (3 single degree of freedom attitude gyros, 6 rate gyros and an accelerometer).
- A display to hopefully allow a manually controlled reentry (a two degree of freedom gyroscope and an accelerometer).

This gives us a system with 13 gyroscopes and 5 accelerometers, all notoriously trouble prone instrument types.

NASA, experienced companies and the MIT Instrumentation Laboratory are now all committed to a guidance and control system design that is fairly conventional. At the same time, no one can identify a path to fit it all into the spacecraft and make it work.

To digress for a minute, I arrived at NASA in mid 1962 fresh from working on nuclear weapon design and reliability to go to work supporting flight crews in the Crew Systems Division. I knew virtually nothing about space. My assignment was to follow the guidance and control work. My only relevant experience was with radar and control systems used to shoot down airplanes with 90mm guns (this was something one did not mention around pilots, and pilots were everywhere[11]). With all the experienced heavy hitters around, I felt very much out of my league.

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[11] In addition to the astronauts, my immediate boss was an ex WWII P-47 fighter pilot, and his boss had flown everything from fighters through four engined B-29s.

In the round robin meeting at Honeywell, the light bulb came on for me that the Block II Command Module would be much simpler, lighter and more reliable if there could be a few changes to the existing approaches.

> The first change would be to extend the MIT/IL Apollo Guidance Computer (AGC) to include a digital autopilot (the DAP). While this would require some additional interfaces to the computer, it would eliminate most of the redundant electronics in the NAA/Honeywell stabilization system – and eliminate three (3) rate gyros.
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> The next change would be to add circuitry to the Honeywell system to extract angular rate data from their backup attitude reference gyros, and then eliminate the three (3) remaining rate gyros.
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> A third change would be to use the Honeywell backup accelerometer and attitude gyros to also provide sensor data for the backup reentry display – and eliminate the Autonetics gyro and accelerometer, at the expense of a little more circuitry.
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> The final change idea came from the MSFN ground radar vs. on-board optics controversy. If MSFN radars could provide backup navigation, why did we need two primary Apollo Guidance Computers, when the second contributed very little to on-board system reliability? Why not just declare the MSFN the primary navigation sensor, eliminate the second computer, remove the on-board navigation sightings from the crew's normal workload and leave the optics as the backup system?

Putting it all together, it looked like we might be able to save weight, simplify redundancy management, eliminate one computer, two gyro types, seven (7) gyros, one accelerometer type and one accelerometer and reduce the overall parts count – at the cost of some additional design effort and software.

> Being 29, and a very junior GS-13 with no G&N credentials, I didn't have the nerve to say anything this heretical during the round robin review. Back in Houston, I did some homework on the Minuteman-I[12] digital control system and

[12] Minuteman-I: The first U.S. solid fueled intercontinental ballistic missile, circa late 1950s.

> created comparative reliability diagrams to see how just how crazy the ideas were. It was obvious that the dynamics of the Command and Service Module were not as demanding as a Minuteman launch, and the Block II AGC was much more capable than the Minuteman disk-based serial computer.

The tangible benefits looked like a saving of 100+ pounds dry weight, a simpler system, better reliability, more flexibility for unknowns and probably lower costs – if all the changes could be made.

Several weeks later, I was in one of those typical big program review meetings and sat next to Cliff Duncan.[13] Part of the meeting involved hand wringing over what to do about the stalemate in resolving the NAA/Honeywell design issues. During a break, I screwed up my courage, talked to Cliff and briefly sketched out the set of changes that might solve the NAA/Honeywell design problem, and what the benefits might be.

> Passing on these "ridiculous" concepts was only possible because I did not work for Cliff and I was not a part of the Guidance and Control chain of command.

I've always been grateful to Cliff that he didn't look at me as if I was a total nutcase and walk away. Much to my surprise, he asked for a meeting and more details. What I remember about the next month or two is:

- The MIT/IL management didn't think they could add digital flight control to their system, at least in part because they felt they already had too much to do.
- The NASA Houston flight controls people were sure a digital autopilot (DAP) could not work for a manned system.
- Joe Shea decided he could solve some of the Command Module weight and configuration problems he was facing by eliminating a computer, adding digital flight control to the remaining primary G&N computer and assigning MSFN the primary navigation responsibility.

[13] Chief, Guidance and Control Division, NASA, MSC.

- In March or April, of 1964, Joe brought the North American management to Houston and told them, in no uncertain terms, the configuration changes they, MIT/IL and NASA were going to make.

At the time, I thought my arguments were what convinced Cliff and Joe. What I now know is that they did not need much convincing that a DAP was technically feasible. Cliff knew from his DARPA experience. Joe knew because he sold the Air Force on using digital flight control for the Titan II guidance system when he was with AC Spark Plug,[14] and then managed the development program. All that was been needed was the idea to apply DAP technology to the Apollo situation, and an estimate of the benefits.

What I don't know is what, if any, closed-door discussions went on to test the waters, or prepare the way, with other NASA senior management. Whatever they did, I am sure that both Cliff Duncan and Joe Shea were critical to the decision to go digital.

After the decision was made, Cliff sent me to Cambridge, alone, to break the news to the Instrumentation Lab senior people.

> This is a meeting I will never forget. It was in a large office at 75 Memorial Drive and my memory is that Ralph Regan, Dave Hoag, Milt Trageser, Dick Batten and possibly John Miller were there. My job was to break the news that Milt's space navigation approach was now the backup, instead of the primary system, Eldon Hall's redundant computer was being eliminated and that we needed them to add digital flight control hardware and software to the AGC. As they all asked questions and attacked the logic behind the changes, I could feel myself shrinking to a midget among giants. In the end, they accepted the DAP challenge, made it all work and we became good friends.

One humorous part of the story is the reaction of the NASA MSFN people when the decision was announced that their system would be the primary navigation source. After arguing about how MSFN would be more accurate than the on-board sextant and

[14] AC Spark Plug Division of General Motors, in Milwaukee.

computer, they were taken aback a little as they realized they were now in the primary role and their MSFN had to be a good as advertised (and it was).

With the Command Module DAP decision made, the next step was to look at the Lunar Module. Since the AGC was also going to be used in the LM,[15] it seemed to make sense to take advantage of the built-in DAP capability to save the weight of a set of rate gyros and the redundant flight control circuitry. Plus, with a DAP, there was the potential to save some fuel.

The Grumman flight control people knew in their hearts you could not control a vehicle as agile as the LM with a digital system as slow as the MIT/IL LGC. Plus, like all good engineers, they did not want to lose technical control over a core part of their vehicle and let it go to MIT/IL.

DAP for the LM came to a head around May, 1964, with Grumman presenting the results of their analyses and simulations in the Guidance and Control Division conference room in Houston. They did a very professional and thorough job of analyzing the dynamics, implementing their LM control logic for the LGC and determining that this would require ~90% of the LGC cycles.

> When Grumman finished, all I could think of was “there must be a flaw in their argument because, if they are right, how am I going to ever live down pushing such a flawed concept?”

The next speaker at the meeting was George Cherry from the Instrumentation Laboratory. George started by saying the Grumman people were absolutely correct, implementing an analog design in the LGC would use most of the throughput. His next comment was that if the design is done to take advantage of how a digital computer works, it would only take about 10% of the LGC cycles. George went on to describe the digital design and the simulation results. With this, Grumman appeared to relent and the DAP was primary for the LM as well.

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[15] In the Lunar Module, the AGC was called the LGC, for LM Guidance Computer. The hardware was the same, only the name changed.

Even though the decision was made, there were still people absolutely convinced the DAP decision for the LM would not work. A month or two later, I ran into one of the astronauts in the hall, and he was not happy. When he started talking, I felt back in the Army being chewed out by an expert, only this time the subject was my malfeasance in switching the LM to digital flight control. I was told in no uncertain terms that Grumman convinced him the DAP would not work, would kill pilots and that he would not fly with it. He went on to land on the moon with the LGC between his hand controller and the various engines, and praised the performance of the DAP.

As the systems were being developed, questioning of the DAP decision issue made it all the way to the President's Scientific Advisory Council (PSAC). I wish I could still find the presentation material I used for the PSAC meeting where this was reviewed. I think this was the last challenge to using digital flight control for Apollo.

The rest is history. The DAP did improve mission flexibility and saved weight and fuel. It did reduce the crew's workload. It certainly shortened the time to the first landing on the moon. Last, but not least, the LM DAP made it possible to use of the LM engine for the Apollo 13 rescue.

We owe Cliff Duncan and Joe Shea a tribute for their courage in moving to digital flight control. Without them both, I doubt that it would have been even considered, and I'm sure a DAP for Apollo would never have been approved.

Once digital flight control was launched, it was people at NASA, MIT/IL and other contractors who did the hard work and accomplished the miracles to make the DAP a reality – and it worked every time. My heartfelt thanks to all of them.

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