Inside Apollo: Heroes, Rules and Lessons Learned in the Guidance, Navigation, and Control (GNC) System Development

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INTRODUCTION

I am writing this in March 2019 which is halfway between the 50th Anniversary of Apollo 8 (Dec 1968) and Apollo 11 (July 1969). Those 2 flights were among the greatest explorations of mankind. In 8, astronauts deliberately put themselves in orbit around the moon expecting the rocket engine to later fire and bring them home to Earth. In 11, it was mankind's first visit to the moon and Tranquility Base. Movies, books, articles, and documentaries have covered the space race. I will give you my thoughts based on 10 years inside the GNC program design, many hours in the Spacecraft Control room at Cape Kennedy monitoring GNC performance through liftoff, and then providing real-time mission support to NASA from MIT in Cambridge, MA.

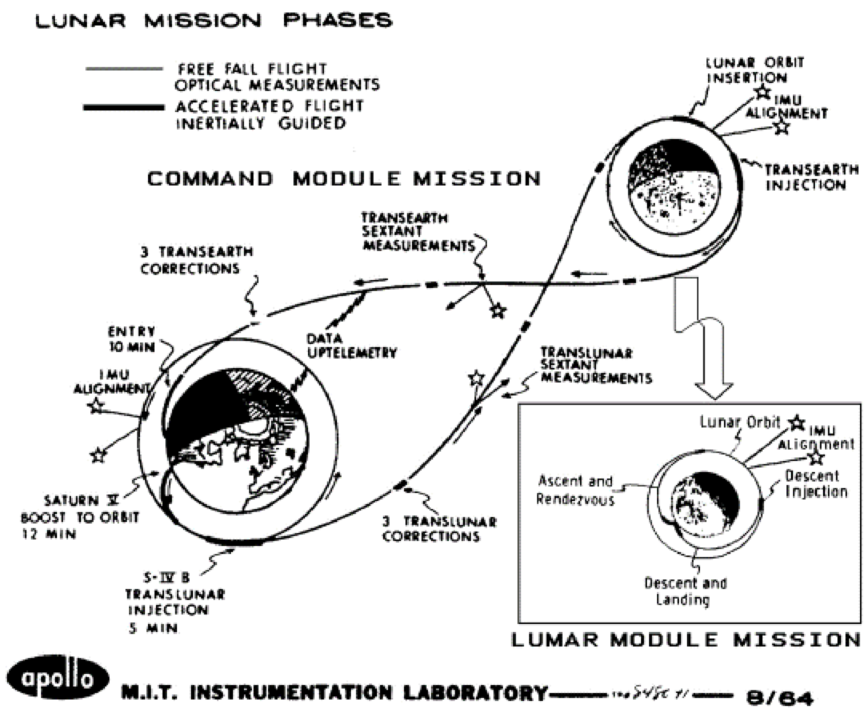

Fig. 1 Lunar Mission Phases

Fig. 2 Earth Rise as Apollo 8 Came Out from Behind the Moon (Dec. 1968)

BACKGROUND

On May 25, 1961 President Kennedy urged the nation to commit itself to landing a man on the moon before the decade was over. He was a visionary who believed in science and engineering and his technical advisors. He made this decision even before the US had put anyone into Earth orbit! In August 1961 NASA awarded the **first** Apollo contract to the MIT Instrumentation Laboratory (MIT/IL or I-Lab), directed by C. S. Draper, who was the Head of the MIT Department of Aeronautics and Astronautics. This contract was given even before the contract for the Saturn booster rockets was given to Wernher von Braun at Huntsville. How come it was given to a university? One reason was the I-Lab had developed inertial guidance (which was being used in all US ballistic missiles) providing a way for the astronauts to complete the mission without radio updates from the ground. NASA was worried that another country would attempt to jam the signals and wanted a way to make sure the astronauts could make it back home safely. (No jamming was ever attempted, but recent news reports claim that another country has been jamming/spoofing GPS signals during NATO exercises and elsewhere.)

In Sept 1961 I was entering my sophomore year at MIT and heard about the Apollo contract. I rushed over to Dr. Draper's office and asked if I could join his Lab and he said sure "Go see Eleanor." I guess I liked the place a lot and eventually retired 46 years later.

Fig. 3 President Kennedy

Fig. 4 At the I-Lab, Doc Draper Explains Apollo Guidance to von Braun (my boss A.Laats in headphones)

HEROES

Jumping ahead to 1965, we were well on our way to building the first prototype GNC and were regularly visited in Cambridge by astronauts for updates and training. The astronauts were the brave heroes who rode on top of the Saturn rockets. I was in the System Test Group where all the system elements (on-board computer hardware and software, inertial system, optics for star sightings, and much more) were put together and tested as a system. The Group did prototype testing in Cambridge, supported launches at Cape Kennedy, and supported the Johnson Space Flight Center in Houston via a real-time mission support link to the I-Lab. During several launch sequences I was in the Spacecraft Control room at Cape Kennedy and when my 12-hour shift was over, I went to the Press Section viewing center 3 ½ miles away from the launch pad to see, feel, and hear the rocket blast off. It was really like a science fiction event, including the coverage by all the TV news-network anchors on their raised platforms. (Walter Cronkite was my favorite.)

The best experience was during Apollo 11. The Spacecraft Control room was on the second floor of the Manned Spacecraft Operations Building. We shared the second floor with the astronaut's quarters. That's where they lived before the missions, dressed in space suits, and took the elevator down to the ground floor to go outside and get into the van to the launch pad. Everyone has seen the pictures of them coming out and climbing into the van. That day I took the stairs down and went outside with a borrowed movie camera. With so many spectators there, all I could do was to hold the camera above my head and hope for the best. Then I went to the Press Section and took more film of all the I-Lab people gathered there. At home I discovered I had perfectly filmed the astronauts and their faces showing through their visors. Quite a home movie, to say the least. (If you see the recent movie Apollo 11, I am in that crowd.)

And then there were the I-Lab technical heroes. I recall we had staffed up to around 500 people working in a building near MIT. It seemed to me that I was surrounded by the smartest people you could ever hope to work with and I still feel that way. It is impossible to name everyone and their contributions. I am just going to single out one now, James Potter, for his legendary contribution. The guidance computer was a fixed-point machine with limited word length. The fundamental way that mid-course navigation was to be performed was with a Kalman filter. Simulations had shown that the filter could diverge because of the finite word length. The story is that Potter learned of the problem on a Friday in 1962 and returned on Monday with the solution: the square-root filter which worked with the square root of the correlation matrix thus doubling the precision provided by the guidance computer. (See Battin, Astronautical Guidance, Problem 9.11, McGraw Hill, 1964)

Fig. 5 Command Module (CM)
Docked with Service Module (SM)

Fig. 6 Lunar Module (LM)

THE CRITICAL HARWARE ELEMENT– THE APOLLO GUIDANCE COMPUTER (IEEE MILESTONE, 2011)

The Apollo Guidance Computer (AGC) had to be extremely reliable with enough capacity and speed but in a small volume, weight, and size (1 cubic ft). Early in the development, the onboard software demands of developing an autonomous system with an astronaut interface began to be understood. Using the available technology, some estimates resulted in an eventual computer size as large as the Command Module itself. That obviously would not do.

In 1962, a decision was made to use integrated circuits which were then in their infancy. In 1963 the I-Lab was conducting an intensive integrated circuit test program consuming about 30% of the entire US output. In 1964, further justification of the choice happened when the AGC was also tasked to do all the autopilot functions. That alone used about 10% of the memory and 30% of the computation time in certain mission phases. Many different autopilot modes were required depending on the various configurations (Service Module (SM), Command Module (CM), Lunar Module (LM)) of the 3 vehicles. I recall there were 16 independent thrusters, obviously more than any person could control. The AGC digital control laws were very complicated and even involved a non-orthogonal set of control axes. This was the first digital autopilot (i.e., fly -by-wire) of an aerospace vehicle. The computer never failed and always did exactly what it was supposed to do in flight. (One of the astronauts in a training session was sort of overcome with all the complicated things that the AGC could do, that he stated he was going to turn that sucker off in orbit and get back to the old ways of doing things. He finally came around.)

Fig. 7 Apollo 8 and 11 Astronauts I-Lab Training (Seated L -R: Lovell(8), Borman(8), Collins(11), Anders(8), Armstrong(11), Aldrin(11))

For the second lunar landing mission, Apollo 12 in November 1969, I went out of the Control Room to the Press Section to watch the launch on a very overcast day. Right after clearing the tower, the booster was struck by lightning. Then it was struck again. When I got back to the Control Room, I asked what happened. I was told there were two lightning strikes but the computer instantly restarted after each. (I wish my Windows computer would work that fast! Especially when it quits because of simple static electricity.)

The software effort for the computer was very underestimated at the beginning of the program. As the lunar missions became closer, more effort was required to develop the software to meet the various mission requirements. My understanding was that a total of 1400 man-years of software effort were expended with the peak effort in 1968 at 350 man-years. Margaret Hamilton led a team of developers in coding and verifying that requirements were met. This was carried out through testing of individual programs and then the collection of programs and, ultimately, with the actual hardware in the Systems Test Laboratory. This was the ideal situation.

However, in the early days of the program, software development was more chaotic in the sense that individual engineers were developing the requirements for their own areas of responsibility, doing their analyses, programming the AGC, and evaluating the results. There was nothing top-down about it. This was true for many fundamental mission segments which were common to every mission. For prelaunch alignment and calibration, every mission needed that. I recall one day a software documentation person came into my office and asked where the requirements were documented. I told him they were in my head as my boss had told me to figure out how to calibrate and align the system on the top of the booster while there would be vibrations and movements from solar heating, winds, fueling, etc. Then the visitor asked about flow charts of the program. Never had time or reason to draw them, I answered. At some point, I was asked to explain the very many AGC stored constants that my program needed so they could document each line of the computer code listing. I tried to explain they were related to the pre-computed gains of the 13-state Kalman Filter I had designed. That was too much and off he went. In the end, a documentation team generated a report of what was actually coded, and standard flow charts were prepared by another team. I named the collection of constants “magic numbers” and you can find them listed as that, in the programs for every flight! (Our wonderful leader Dick Battin would chuckle about what I did. Do an internet search on Apollo Guidance Computer (AGC) and you will find the “magic numbers” somewhere in the listings.)

Fig. 8 Schmidt Uploading Magic Numbers?

There certainly was never any intension to make software changes in-flight but the capability existed. Such an emergency occurred on Apollo 14 about 3.5 hours before descent to the moon. A faulty abort switch was sending signals which would have caused an LM abort during the descent and a return to the orbiting CM/SM. Engineers in our Cambridge I-Lab support room immediately started working the problem. A solution was proposed by Don Eyles and rapidly tested and then sent to Houston for further testing and communicated to the astronauts. They had only 10 minutes after receiving the procedure to start using it during the descent. They landed successfully and exactly where they were supposed to land.

Fig. 9 Real-Time Mission Support at the I-Lab (L-R: back of Tvibutas, Schmidt, Sears, Hamilton, Rye, Laats, and Turnbull)

The computer programs were designed to work with astronaut inputs for both commands and data. Multiple programs were allowed to operate asynchronously and each was assigned a task priority. The highest priority was the most important. During the descent of Apollo 11, one of the astronauts left the rendezvous radar switch on, which resulted in high-rate pulse rate signals being sent to the computer. Near landing the computer was overloaded by these extra signals and caused the computer to restart and display alarm code 1202. However, both Armstrong and the ground controller recognized the problem and knew the computer would keep the essential programs running. The landing proceeded despite the great distraction the alarms caused.

As in the previous example, human errors are always possible. Margaret Hamilton tells the story of how NASA assured her the astronauts would never mess up with an input to the computer so there was no need to make sure they could not ask the computer to do a task inappropriate to that phase of mission. In Apollo 8 during midcourse between the Earth and the moon, Lovell started to do some star sightings for navigation purposes. He meant to tell the AGC that he was using star number 01, but he instructed the computer to run Program 01, my Earth pre-launch alignment program. The computer started generating commands to reorient the inertial system for launch instead of holding a stable position for star sightings. It took a while to undo the mischief this caused and to get the inertial system to the proper orientation.

RULES

During my time on the Apollo program, there were two rules I learned which I have tried to carry throughout my career: (1) no unexplained failures anywhere and (2) always consider other scenarios – "What if?" An example follows. I was running the latest version of my software for prelaunch alignment and calibration in the System Test Lab. I keyed an entry into the GNC system display and keyboard and the AGC "froze up." Putting aside the temptation to simply restart the program, I thought "What if?" this happened when an astronaut keyed in an input during a critical mission phase, or worse to me, it might happen while I was at the Control Room console at Cape Kennedy. Yikes! The whole world would be pounding on me! I quickly gathered as many local gurus as I could find but no one could figure it out. We did a restart and the system operated OK. But now, we had an unexplained failure to resolve. We duplicated it by programming a set of pseudo keystrokes to be applied to the computer continuously and, after several days, the AGC locked up again. We could not figure out where the computer locked up, only that it did. Determined, we built a test rack of equipment over the next several weeks that would generate pseudo-keystrokes and record the last 100 memory locations visited by the computer. Then we tried it out. Success! The computer eventually locked up. Word spread and quickly we had all sorts of experts with their massive computer listings trying to figure out what happened. It turned out there were certain operations within the computer code that could not be interrupted and those sections of code were protected by an INHINT instruction and when the critical code operation was done, a RELINT instruction was used. Somehow in about 36,000 lines of code, an INHINT was misplaced by one line of code! (A similar problem with a missing hyphen in a computer program caused the loss of Mariner I at the start of its mission to Venus on July 21, 1962.)

In Apollo 13, all hell broke loose with the explosion of the Service Module (SM) requiring the crew to power-down the Command Module (CM) and retreat to the Lunar Module (LM). The injured combination swung around the moon but needed to get back on a safe return to Earth trajectory. The only propulsion available was the LM. No one had ever tested the docking collar between the LM and CM/SM on being able to survive the LM pushing the much heavier CM/SM combination. Someone, thankfully, had asked "What if we had to do that" and software had been written and installed in the AGC. That important rocket burn was successful and the crew was on its way to safe return to Earth.

In that same mission, no one had ever thought the CM guidance system would have to be powered down to conserve power for several days while the crew lived in the LM. The temperatures in the CM got to near freezing and there was great concern that the gyros in the GNC would not even spin up. The gyros had to be maintained with heaters at 147 deg F so the viscous fluid enclosed would provide the proper damping. But they did spin up and the accuracy of splash down was within 1 mile of intended.

LESSONS LEARNED- MODELING ERRORS

In general, I learned how to work within a dedicated team of very smart people, asking for help when I needed it, and giving it when I could. No one had done anything like this previously so we were all becoming experts in our particular areas. I became an estimation and control expert developing a real-time on-board 13 state Kalman filter to do the prelaunch alignment and calibration of the inertial system. It was a first of its kind. This was when I learned how modeling errors can upset the best system design with serious consequences.

Our MIT systems were prototypes using sensors (gyros and accelerometers) that we built. However, the equipment provided to the actual spacecraft were built by various industrial contractors to our specifications. Apollo 7 (October 1968) was the first manned flight of the newly redesigned Command Module. During prelaunch testing using my programs in the AGC, the calibration results were erratic. All NASA could do was to replace the inertial system in the Command Module on the launch pad on top of the Saturn- a horrendous undertaking. When they took that system back to the manufacturer's test lab, they could not reproduce the results nor figure out what was going on. Of course, they wrongly blamed the results on my test program in the AGC. This may have happened twice. The President of that company wrote a letter to Doc Draper complaining we were causing them all sorts of problems. Doc sent the letter to my boss, Ain Laats, who sent a response to Doc titled "Can Kalman Filtering Cause Gyro Drift?" Everyone should have a supportive boss like I had. Of course, they eventually figured out that the manufacturer was providing accelerometers that had a dead-zone in output near a zero-acceleration input condition. Since the accelerometers were used as the near-zero measurements in the Kalman filter, it was not surprising the filter diverged. The manufacturer was also using its own test software, not the software used in the AGC. We solved that problem and the manufacturer's woes by keeping the inertial platform slightly misaligned from level such that the accelerometers always had a significant input from measuring gravity while calibrating the system.

A more visible modeling error occurred in Apollo 5 (January 1968). This was the first test of an unmanned LM in Earth orbit. The AGC was programmed to perform several burns of the main engine. In conducting the first burn, the LM thrust level did not build up as fast as was modelled in the AGC, the modeled time constant was incorrect, so the AGC shut the system down as set by a safety criterion. The problem was not immediately recognized on the ground and the remaining burns were controlled by a simple backup system. NASA announced that all primary objectives were met and the AGC functioned flawlessly. True enough. But this was the first time I experienced government "spin". My perspective in the Control Room was the vision of the LM last seen heading towards the South Pole with its main engine on and tumbling end over end because it ran out of attitude stabilization fuel. That must have been a great firework show to the penguins in the Antarctic.

FINAL WORDS

It was a great decade of learning and doing at the same time. I received an SB, SM, and Sc D in that period while working at Doc Draper's I-Lab. If he were alive now, I am sure his comment on jamming of GPS would be "I told you radio navigation was no good. You must use inertial always."

In 1973, MIT cast the I-Lab off on its own after having renamed it the Draper Laboratory. Doc's actual comment was "When the Red Sox fired their manager Dick Williams, they didn't rename Fenway Park after him."

At an AIAA Fellows meeting a few years ago, I was speaking with Buzz Aldrin. He and I had the same ScD thesis advisor W. Wrigley at MIT. I asked him what he thought of NASA's Return to Moon Program. His response was "the astronauts will have to learn Chinese."

I always tried to look ahead in my career and not back through the "rear window." But every once-in-a while certain events would happen to call up the past, like all this 50th celebrating. It was a privilege to be part of a great team at the I-Lab. I am even prouder of their later individual achievements in industry, government, universities, and at Draper Lab. And, especially of Margaret Hamilton who led a team of software developers, coined the term Software Engineering, and was awarded the Presidential Medal of Freedom in 2016 by President Obama. I would frequently go into the I-Lab on weekends to check on my computer simulations that ran over-night. I could almost be sure that she would be there working on her tasks with her young daughter next to her.

There is a former Apollo engineers e-mail distribution that now numbers about 150. I am looking forward to seeing many of them at MIT's March 50th year celebration and Draper's celebration later in the year. All of us have changed from our 20s to 40s when we did the work, to 70s+ today and some are hard to recognize. We fondly remember our leaders and colleagues who have already gone up to the stars.

Fig. 10 July 24, 1969 Apollo 11 Splashdown Party MIT Faculty Club (Standing L-R: Schmidt, Fitzgibbon, Battin, Levine, Hall, Martin)