Apollo Guidance System

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Topics

- A little background history
- Multiple systems:
  - “Primary Guidance and Navigation Control System”
    - Computer
    - IMU
    - Optical alignment system
    - Human interface
  - Other systems
- Summary, tidbits

Some Personal Background

While recovering from an auto accident at the beginning of the Covid-19 pandemic, I spent some time in Assisted Living. I was given 500mL bottles of water, and it occurred to me that with today's technology, we could probably cram the entire Apollo Guidance System into the empty bottle. So, I decided to look into the idea...

Early Story

- Cold War
- Sputnik, and Yuri Gagarin, shocked U.S.
  - Sputnik: October 4, 1957
  - Gagarin: April 12, 1961
- Mercury program started under D. Eisenhower
  - Alan Shepard, suborbital flight, May 5, 1961
  - Early Apollo concept as follow-on, early 1960
  - John Glenn: February 20, 1962
- JFK set man-on-moon goal on May 25, 1961

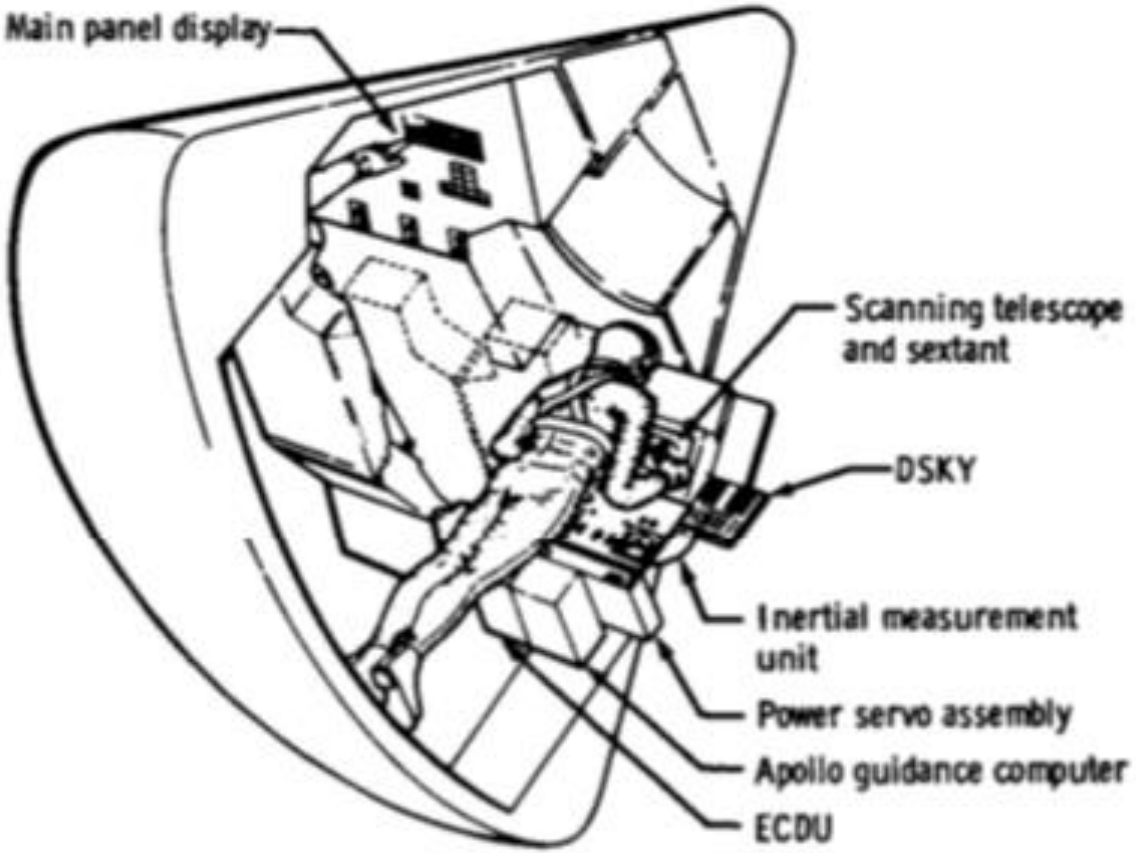
Initial Development

- Quickly realized that “on-board” navigation/ guidance was needed to land on Moon
  - ~3 seconds signal round trip delay (line of sight)
- MIT Instrumentation Laboratory (Draper Labs)
  - Charles Stark Draper
  - Worked on Polaris submarine-launched missile
    - ~1400 mile range, 50% hit in ~1.1 miles (initial version)
      - Roughly “as the crow flies” San Francisco to Oklahoma City
  - Lead in developing Apollo Navigation System

Apollo Guidance System

- “Primary Guidance, Navigation, and Control System”, or “PGNCS” (pronounced “pings”)
  - Command Module and Lunar Module each had one, though with some differences
- Two others:
  - Abort Guidance System (AGS) on Lunar Module (as backup)
  - Saturn Rocket had its own guidance system
- Plus ground-based data

PGNCS location in CM



Portions of PGNCS

Four main portions:

- Computer (AGC)
- Inertial Measurement Unit (IMU)
- Optical Alignment Telescope
- Human Interface

Plus things like mechanical frame, power supplies, cooling, etc.

Apollo Guidance Computer (AGC): Some Highlights (Block II)

- 2K words RAM
- 36K words ROM
- 2.048 MHz clock rate
- 11.72μS memory cycle
- Hardware multiply & divide

Things that seem odd today

- 15 bit word size + 1 bit parity (odd parity)
- One's compliment arithmetic
  - Implies both “positive zero” and “negative zero”
- Fixed point real numbers (as opposed to floats)
- “Paged” memory

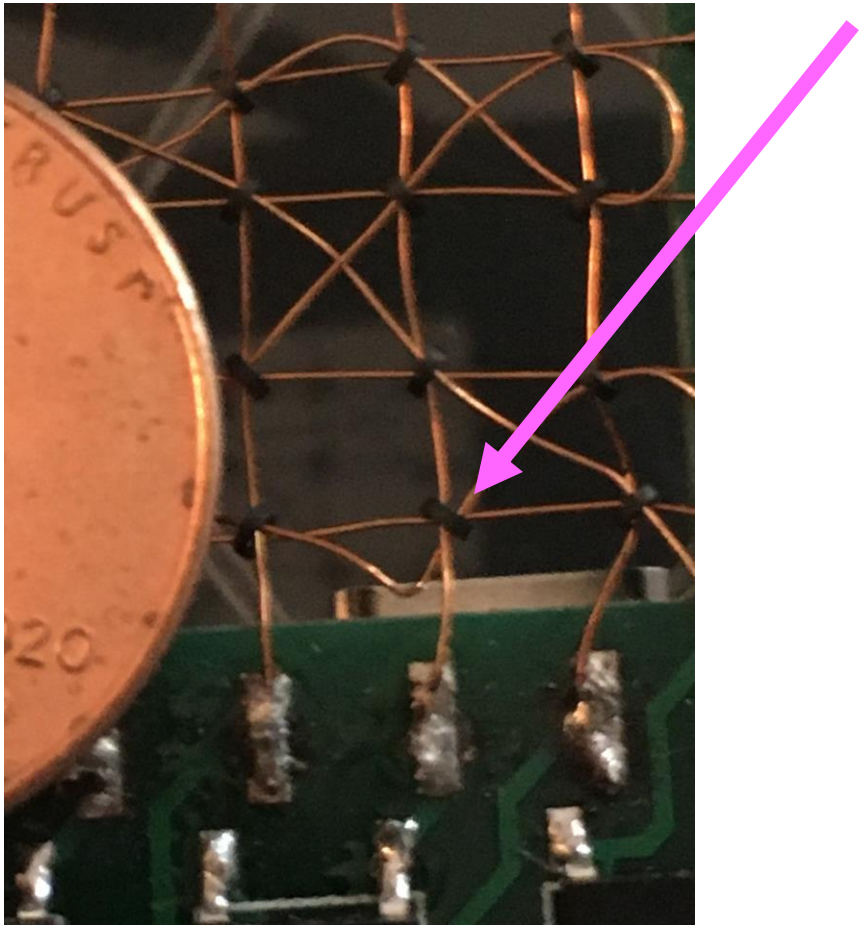
AGC's RAM & ROM

- RAM (read/write memory, aka “erasable”) was magnetic core memory
  - Non-volatile memory (doesn't “forget” when power is turned off)
  - Has destructive read (has to be re-written every time it's read)
  - One core per bit, 16 cores per word
- ROM (read-only memory, aka “non-erasable”) also magnetic core memory!
  - “Rope memory”, one core per word*, not per bit

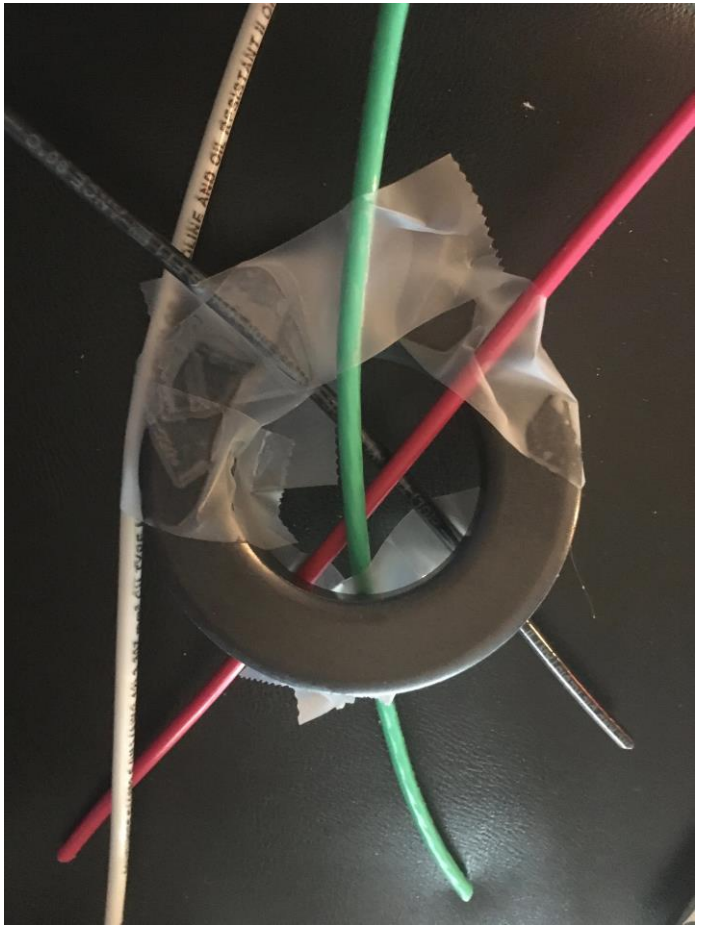
How Magnetic Core Memory Works

- Each core is a small “donut” of a material that can be magnetized
  - RAM: ~0.06” Outside Diameter, ROM: ~5/16” OD
- Every core has two “drive” wires through it
  - RAM has one sense wire through the core
  - ROM can have many sense wires, more drive wires
    - Through a core indicates a “1”, not through is “0”
- Drive wires used to “flip” core's magnetic field
  - Sense wires are used to tell difference when it flips

Example of Core Memory (RAM)



Handwaving: Core Memory



AGC Hardware

- First computer made with silicon ICs (aka “computer chips”)
  - Block I (first version) had ~4100 ICs, each with 3 transistors (mostly part #µL9903)
  - Block II (second version) had ~2800 ICs, each with 6 transistors (mostly part #PL9939)
  - Nearly all were 3-input NOR gates, all were RTL
  - Consumed ~60% of world output of ICs during 1963
  - Each IC cost $20 to $40 (about $200 to $400 today)

AGC Hardware (continued)

- Highly modularized
- Original design to be repairable in flight, abandoned after Apollo 1 fire
- Block II used for all manned flights
- IC connections were welded, not soldered
- Intermodule connectors wire-wrapped

AGC Software

- All software written in Assembly Language
- Had a “real time interpreter”, what today we'd think of as a suite of subroutines
- Each flight had unique software, though much was copied from previous flights
- Took ~2 months to program the core rope-memory ROMs
- Used a main-frame to emulate ROM

Inertial Measurement Unit (IMU)

- Provides info on:
  - Orientation (attitude or direction)
  - Rate of rotation
  - Acceleration
- An IMU has gyroscopes and accelerometers
- By “integrating”, can keep track of position
- Important note: they ALWAYS “drift” over time

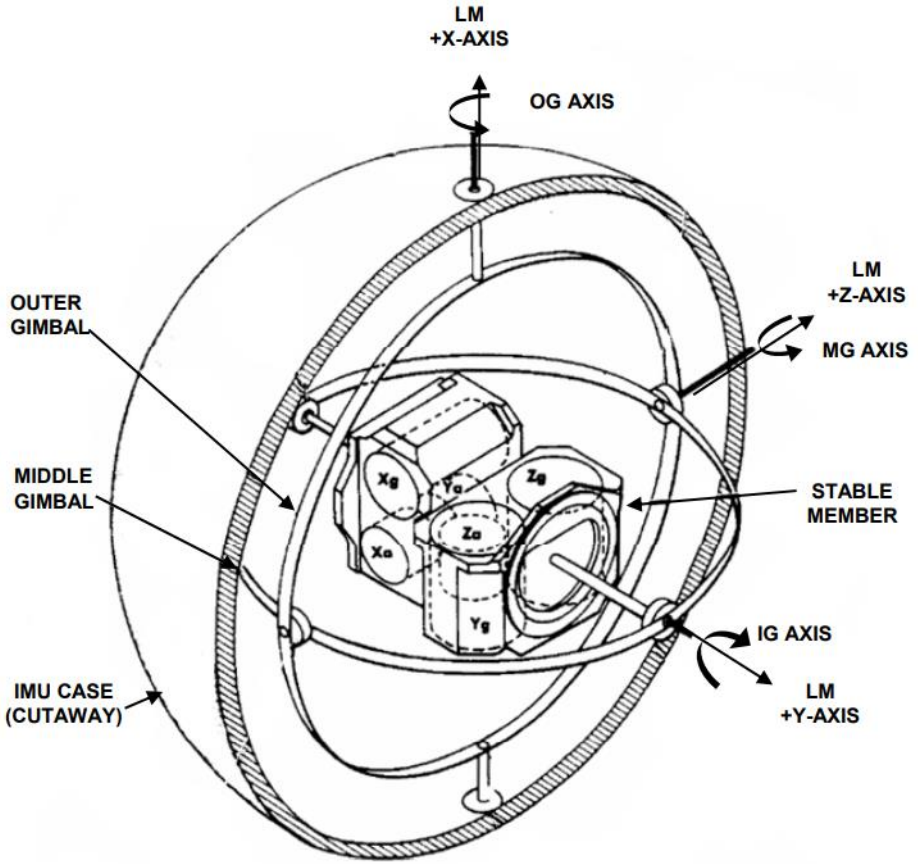
Apollo IMU - Specs

- Initial specs for Apollo:
  - Gyros accurate to ~0.01° of arc
    - Max rotation rate 720°/sec
  - Accelerometers accurate to “about 100 PPM” (or 1 part in 10,000)
    - Max +/- 16G
- In today's terms:
  - 15 bits for gyros
  - 13 or 14 bits for accelerometers

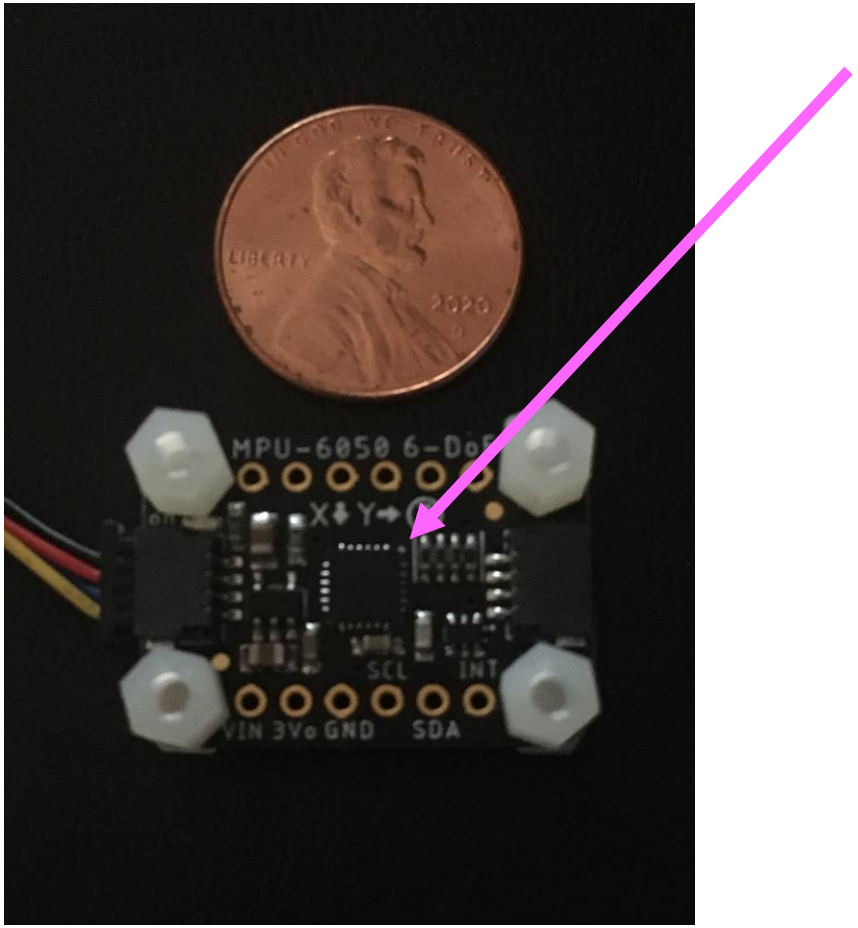
Apollo IMU

- A sphere, a little smaller than a basketball
- Polaris gyros accurate enough, but needed other upgrades for duration and manned flight
- Apollo accelerometers based on Polaris design, with significant improvements

Apollo IMU


LM
+X-AXIS
OG AXIS
LM
+Z-AXIS
MG AXIS
OUTER
GIMBAL
MIDDLE
GIMBAL
STABLE
MEMBER
IG AXIS
LM
+Y-AXIS
IMU CASE
(CUTAWAY)

Modern IMU



Optical Alignment System

- Here is where the hardware for CM and LM systems differed greatly
- Command Module:
  - Precision sextant (SXT) for measuring between stars and Earth or Lunar “landmarks”
  - Wide angle “scanning” telescope (SCT) for star sightings
- Lunar Module:
  - Only one telescope for taking star sightings

Optical Alignment System

Note that alignments (star sightings)

were done MANUALLY!

That means that the optics had to be

usable through the faceplate

of a spacesuit!

Human Interface

- “Display and Keyboard”, or “DSKY”
  - 2 in CM, 1 in LM
  - LM also had an altitude indicator for commander
- Display was green electroluminescent
  - Could display 3 numbers of sign and 5 digits
  - Segments driven by electromechanical relays
- Although data was internally metric, displayed in U.S. Customary Units (inches, feet, etc.)
- First of kind calculator-like interface

Other Guidance Systems

- LM had separate “Abort Guidance System”
  - Built by TRW
  - In case of PNGCS failure, could guide LM to orbit
  - Used in Apollo 13 as required less power and cooling than PNGCS
- Saturn V rocket had it's own guidance system, installed in 3rd stage
  - Sensors and controls throughout rocket
  - Could communicate with CM PNGCS

Summary and Tidbits

- Navigation systems critical to Lunar missions
  - Many early probes meant to crash on Moon missed
    - Both U.S. and Soviet missed Moon completely
- Huge push to IC industry
- Gov't spent about same $ on:
  - Entire Apollo program
  - Viet Nam War in 1968 alone

More Tidbits

- Prior to any human probes, Moon had a primordial atmosphere
  - About the same mass as the fuel load for a single LM
  - So, current Lunar atmosphere is more than 7/8ths rocket exhaust – talk about POLUTION!
- Apollo 11 had two “alarms” during landing
  - Eventually traced to having ascent radar turned on
    - I can see two reasons for having it on:
      - One less switch to worry about in event of abort
      - 1960s radar needed long “warm up” to stabilize

Questions?