What we hope to accomplish

• AGC Origins and Requirements
• Hardware overview
• Software overview
• User interface
• “How to land on the Moon”!
Command and Service Modules
Lunar Module
AGC Origins

- MIT Instrumentation Lab
  - Now Charles Stark Draper Laboratory
- Early work done on Polaris ballistic missile
- NASA contracted MIT to create AGC
- Vigorous debate on the interaction of man, spacecraft and computer
- As Apollo requirements grew, computer requirement grew even more!
Early Design Issues

- What systems will it interface with?
- How much computing capacity?
- What type of circuit technology?
- Reliability and/or in-flight maintenance?
- What do we *need* a computer to do?
- What does a human interface look like?
AGC Requirements

- Autonomously navigate from the Earth to the Moon
- Continuously integrate State Vector
- Compute navigation fixes using stars, sun and planets
- Attitude control via digital autopilot
- Lunar landing, ascent, rendezvous
- Manually take over Saturn V booster in emergency
- Remote updates from the ground
- Real-time information display
- Multiprogramming
- Event timing at centisecond resolution
- Multiple user interfaces ("terminals")
Logic Chips

- Fairchild introduced the “Micrologic” chip
- Two triple-input NOR gates per chip
- Resistor-Transistor Logic
- Virtually all logic implemented using the Micrologic chips
  - Single component greatly simplifies design, testing
  - Greater production quantities -> better yields and higher quality
  - Several hundred thousand chips procured (!)
Micrologic chips installed on "Logic Stick"
Logic Assemblies

- Subassemblies (sticks) contain 120 chips (240 gates)
- Chips welded to multilayer boards
- Logic boards essentially identical
- Traditional circuit boards could not produce the necessary logic density
- Interconnections made through wire-wraps in the underside of the “logic tray”
Completed “Logic stick”
AGC upper and lower trays

Upper tray: Core Rope and Erasable memory

Lower tray: Logic and interface modules
AGC Hardware

- 36K (16-bit) words ROM (core rope)
- 2k (16-bit) words core RAM
- Instructions average 12-85 microseconds
- 1 cu.ft, 70 pounds, 55 watts
- 34 “Normal” instructions
- 10 “Involuntary” instructions
- 8 I/O instructions
AGC Internal Architecture

- Registers
  - Accumulator, program counter, core bank, return address, etc.
- Input/output channels
- Data uplink / downlink
- No Index register (!)
- No serialization instruction!
- Interrupt logic and program alarms
Logical overview (Spaghetti diagram)
Instruction Set

• The usual suspects – 34 instructions
  – 3 bit opcode, plus (sometimes) two bit ("quarter code"), plus "Extend" mode.

• “Interpreted” instructions
  – Coded in Polish Notation
  – Similar to "p-code"
  – Trigonometric, matrix, double/triple precision
  – *Huge* coding efficiency
Instruction Set

• 8 I/O – read/write through channels
• 10 Involuntary instructions - counters
  – Example: Update from Inertial Measurement Unit
    • Counters represent accelerometer and gimbal changes
  – No context switch!
    • Currently running program *NOT* interrupted
  – Counters updated directly by hardware
  – Processing resumes after involuntary instruction (counter update) finishes
  – Processing delayed only about 20 microseconds
Memory Architecture

- All memory 16 bit words
  - 14 bits data, 1 bit parity, 1 bit sign for data
  - Not byte addressable
- Read/Write memory
  - Conventional coincident-current core memory
  - 2K words
- Read Only Core “Ropes”
  - 36K Read-only storage
  - Contained all programming and some data
Memory Architecture

• Core “Ropes”
  – Read-only storage
  – One “core” reused 24 times for each bit (!)
  – High storage density
  – Software “manufactured” into the ropes
    • Software frozen 10 months before launch!
    • Ropes installed in spacecraft 3-4 months prior to launch
  – 6 rope modules, each 6K of memory
  – Rope modules easily replaced in computer
Core Rope Module
Core Rope Wiring Detail
Addressing memory

- Instruction has 8 to 12 bits for addressing
- Need to address 36K for instructions, 2K for data
- Not enough bits! (need at least 16 bits -> 64k)
- Torturous memory bank addressing
  - “Banks” are either 1K or 256 bytes
  - Various registers specified the particular bank
  - Lots of extra code needed to manage memory banks
Interfaces ("I/O Devices")

- **Gyrosopes and accelerometers**
  - Collectively known as the "IMU" (Inertial Measurement Unit)
- **Optics**
  - Sextants and telescopes used for navigations sightings
- **Radars and ranging equipment**
  - 2 radars on LM, VHF ranging on CSM
- **Engines**
  - CSM: SPS, LM: DPS, APS
  - Both have 16 attitude control thrusters, CM has additional 12 for reentry
- **Analog Displays**
  - "8-Balls", altitude, range, rate displays
- **Display Keyboards (DSKY’s); 2 in CM, 1 in LM**
- **Abort buttons (!)**
I/O Channels

• Mapped as memory addresses
• Accessible only by I/O instructions
• All 16 bits wide
• 7 input channels
• 14 output channels
Man-Machine Interactions

• Hasn’t changed in 50+ years
• Machine instructions
  – Opcode - Operands
• Command line interface
  – Command - Options
• Even WIMP’s use similar philosophy!
• All define an object, and the action to be performed on that object
Using the DSKY interface

- DSKY – Display and Keyboard
- Specialized keys assigned for each function
- Three “registers” displayed data
- Commands entered in “Verb-Noun” format
  - “Verb”: Action to be taken
    - Display/update data, change program, alter a function
  - “Noun”: Data that Verbs acts upon
    - Velocities, angles, times, rates
DSKY – Display Keyboard
DSKY Components

- Electroluminescent digits (not LED/LCD)
- 2 digit displays for Program number, Verb, Noun
- 3, 5-digit displays for data, +/- signs
- No decimal points!
- Keyboard
- Warning lights
- DSKY separate from computer
Using the DSKY interface

• “PRO”: Proceed with the data as offered by computer
• “Enter”, “Clear”: – self explanatory
• “Key Rel”: Releases control of the DSKY to computer (upon computer request)
• “Reset”: resets program alarm
The Apollo Guidance Computer: Architecture and Operation

DSKY in the Lunar Module
Sample DSKY Query

• Programs, Verbs and Nouns referred to by their “number”
• Lots to remember:
  – ~45 Programs, 80 verbs, 90 Nouns
• Example: Display time of the next engine burn
• Enter Verb, 06, Noun, 33, Enter
  – Verb 06: Display Decimal Data
  – Noun 33: Time of Ignition
  – End with pressing Enter
• Notation: V06N33E
Sample DSKY Query: Time of Engine Ignition

Verb 06, Noun 33: Display Time of Ignition

Verb 06: Display values

Program number – P63

Noun 33: Time of Ignition

Hours

Minutes

Seconds . hundredths

Time of Ignition: 104:30:10.94 (Mission time)
AGC Executive

- Multiprogramming, priority interrupt, real-time operating system
- Several jobs running at one time
  - Up to 7 “long running” jobs
  - Up to 7 short, time dependent jobs
- Only one program has control of the DSKY
Scheduling a New Job

• Starting a program requires temporary storage be allocated

• Two storage areas available
  – CORE SET: 12 words
    • Priority, return address and temp storage
    • Always required
  – VAC Area: 44 words
    • Larger temp storage
    • Requested usually if vector arithmetic is used

• 6 CORE SET’s and 6 VAC areas available
Scheduling a New Job

• All work assigned a priority
• Executive selects job with highest priority to run
  – DSKY always the highest priority
  – In exceptional situations, jobs can change priority
• Every 20 milliseconds:
  – Job queue checked for highest priority task
  – Highest priority job allowed to execute
• Jobs are expected to run quickly, and then finish
  – “Night Watchman” verifies job is not looping and new work is being scheduled (every 1.2 seconds)
  – Restart forced if a job is hung up
Error Messages

• Errors need to be communicated to crew directly
  – Software might encounter errors or crash
  – Crew may give computer bad data or task
• “Program Alarm” issued, w/error light on
  – Verb and Noun code indicate type of error
• Depending on severity of error, may have to force a computer restart
Error recovery

- All programs register a restart address
  - Program errors, hung jobs, resource shortages can all force a computer restart
- A “restart” is the preferred recovery
  - NOT the same as rebooting
  - All critical data is saved, jobs terminated
  - All engines and thrusters are turned off (most cases)
  - Hardware is reinitialized
  - Programs are reentered at their restart point
- Process takes only a few seconds!
Landing on the moon

• One attempt, no second approaches!
• AGC handles all guidance and control
• Three phases
  – Braking (Program 63)
    • Started ~240 nm uprange at 50K feet
  – Approach (Program 64)
    • 2-3 nm uprange, begins at ~7K feet
  – Final Descent (Program 66)
    • Manual descent, started between 1000 to 500 feet
Lunar Module Descent Profile

Braking Phase: Program 63

Approach Phase: Program 64

Terminal Descent: Program 66
Program 63: Lunar descent

• Started 10-20 minutes before descent
• Computes landing site targeting
• Started with V37E63E
• Response V06N61
  – Time to go
  – Time from ignition
  – Crossrange distance
P63 Overview

• Verb 06, Noun 33: time of Ignition
  – Hours, minutes, seconds
  – 104:30:10.94

• Verb 06, Noun 62: Velocity info
  – Abs(V), Tig, Accum (Delta-V)

• Flashing Verb 99: Permission to go
  – Key PRO! Ignition!

• P63 displays Verb 06, Noun 63
  – Delta altitude, altitude rate, computed altitude
P63 – Braking phase (Confirm Engine Ignition)

T-35 Seconds, DSKY Blanks for 5 seconds, at T-5, Flashing Verb 99 displayed

Verb 99: Please enable Engine Ignition

Program number – P63

Noun 62: Pre-ignition monitor

Current Velocity

Time to ignition (min, sec)

Delta V accumulated

3 seconds until ignition! Press PRO[ceed]
P63 – Braking phase (post-ignition)

Verb 06, Noun 63: Monitor braking phase of descent

Verb 06: Display values

Program number – P63

Noun 63: Descent monitor

Radar altitude - computed altitude (not valid yet)

Altitude rate

Altitude
P63 – Accept landing radar updates
Verb 57, Enter

Verb 57: Accept Radar Updates

Program number – P63
Noun 63: Descent monitor
Radar altitude - computed altitude (not valid yet)
Altitude rate
Altitude
P63 – Monitoring the descent

Computer displays were compared against a “cheat sheet” Velcro’d onto the instrument panel.

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<th>Time from Ignition</th>
<th>LM Pitch angle</th>
<th>Antenna angle</th>
<th>% Fuel</th>
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</table>
Approach – P64!

- Pitch over the LM to see the landing site
- Program 64 automatically selected by P63
- ~7,000 feet high, 2 miles from landing site
- Key PRO to accept!
- P64 displays V06, Noun 64
  - Time to go, Descent angle, rate, altitude
  - Another cheat sheet velcro’ed to the panel
P64 – Approach phase of landing

Program 64 automatically entered from P63

Verb 06: Display values

Program number – P64

Noun 64: Descent monitor

Seconds until end of P64, and Landing point targeting angle

Altitude rate

Altitude
P66: Terminal Descent

- Final phase – only hundreds of feet high
- Less than one minute to landing
- Computer no longer providing targeting
  - Maintains attitude set by Commander
- Commanders attention is focused “outside” the spacecraft
  - Other astronaut reads off DSKY displays
P66 – Terminal Descent Phase (manual control)

Program 66 entered using usually through cockpit switches

Verb 06: Display values

Program number – P66

Noun 60: Terminal Descent monitor

Forward Velocity

Altitude rate

Altitude
Apollo 11 Alarms During Landing

• During landing, several program alarms occurred during the final minutes of descent
• Aborting the landing was a real possibility!
• Processing unnecessary data put CPU to 100% utilization
  – Unexpected counter interrupts from rendezvous radar
  – Jobs could not complete in time and free up temporary storage
• “1201”, “1202” alarms: No more CORE SET or VAC areas -> Restart!
• Guidance, navigation and targeting data preserved throughout restart
• Restart completed within seconds
• Computer functioned exactly as it was designed!
Abort!  (A bad day at work....)

Pressing the Abort button automatically switches software to Abort program.
Apollo 14 Abort Switch

• Loose solder ball in Abort switch
  – If set, will abort landing attempt when lunar descent is begun
• Detected shortly before descent was to begin
• Need to ignore switch, but still maintain full abort capability
• Patch developed to bypass abort switch
  – Diagnosed, written, keyed in by hand and tested in less than two hours !!
Summary

• AGC was “bleeding edge” technology
  – By the end of Apollo, hopelessly outdated!
  – Still, it was all that was needed
• Techniques pioneered in Apollo are still in use today in “modern” computers
• First time a computer required for mission success
• Best thing: The computer never failed!
Shameless Endorsements

• Infoage Science/History Learning Center
  – www.infoage.org

• The Apollo Lunar Surface Journal
  – www.hq.nasa.gov/alsj

• The Apollo Flight Journal

• Journey to the Moon, Eldon Hall, AIAA Press

• Cradle of Aviation Museum
  – Uniondale, Long Island

• Me!
  – frankobrienvl@gmail.com