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DEPARTMENT: PRODUCT REVIEWS

The Apollo Guidance Computer

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The Apollo Guidance Computer (AGC) is an engineering marvel. The AGC performed all of the necessary computation to successfully guide, navigate, and control the spacecraft, which carried Neil Armstrong and Buzz Aldrin to the surface of the moon back in 1969 as part of the Apollo 11 mission. Weighing in at a staggering 32 kg and featuring a blazing-fast 2.048-MHz clock, it was the first computer to use silicon integrated circuits (ICs). Mankind has made great strides and advances both in regards to space exploration as well as technology since the AGC made its debut. In light of those successes and this year being the 50th anniversary of the microprocessor, it is only fitting that the AGC be celebrated.

The year 2021 is important for mankind's space exploration efforts. Perseverance and ingenuity had both landed on the surface of Mars on February 18. Ingenuity completed the first powered controlled flight by an aircraft on a planet other than Earth on April 19. Virgin Galactic completed the first suborbital flight to carry a civilian (Richard Branson) into space on July 11. Blue Origin followed with a suborbital flight carrying Jeff Bezos and other civilians on July 20. Most recently, on October 13, Blue Origin completed a second suborbital flight, which launched actor William Shatner into space. Mankind is making great strides in understanding space travel and the sustainability of life on other planets.

However, these pursuits are not new. On July 24, 1969, over 50 years ago, astronauts Neil Armstrong and Buzz Aldrin were the first humans to step foot on the surface of the moon as part of the Apollo 11 mission. It is more than fair to say that today's technology is very sophisticated and it certainly contributed to the aforementioned successes we have had in 2021. So you are probably wondering how we made it to the moon way back in 1969 with far less sophisticated technology. Just to put things into perspective, the floppy disk was not even commercially available for another two years! The answer, as you may have deduced by this article's title, is with much help from the Apollo Guidance Computer (AGC).

Given the successes we have had this year and this being the special issue commemorating the 50th anniversary of the microprocessor, it only made sense that we celebrate the AGC.

DESIGN

The first computer to use silicon integrated circuits (ICs),[2] the AGC was designed at the MIT Instrumentation Laboratory under Charles Stark Draper with hardware design led by Eldon C. Hall.[3] The original design, referred to as Block I, used 4,100 ICs each containing a single three-input NOR gate. The revised design, which was used in crewed flights, referred to as Block II, used 2,800 ICs mostly composed of dual three-input NOR gates and several expanders and sense amplifiers.[4] The ICs were manufactured by Fairchild Semiconductor. It consumed 55 W of power and weighed a staggering 32 kg.

The user interface, as shown in Figure 2, was referred to as DSKY, which stood for display and keyboard.

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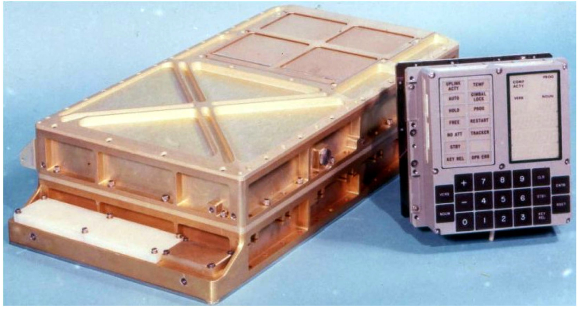

AGC's main casing (left) and the DSKY interface (right).[1]

TABLE 1. Instructions of the AGC. * denotes an extra instruction.

TC	Transfer control
CCS	Count, compare, and skip
INDEX	Add the data retrieved at the address specified by the instruction to the next instruction
RESUME	Return from interrupts
XCH	Exchange
CS	Clear and subtract
TS	Transfer to storage
AD	Add
MASK	Bitwise AND of memory with register A
MP *	Multiply
DV *	Divide
SU *	Subtract

Commands were entered as two-digit words: verb (the type of action to be performed) and noun (which data were affected by the verb).

A 2.048-MHz clock was used as the timing reference for the AGC. A four-phase 1.024-MHz clock used to perform internal operations was produced by dividing the clock by 2. This clock was further divided by 2 to yield a 512-KHz signal used to synchronize external systems. For perspective, the Nintendo Game Boy, released in 1989, had a 4.19-MHz clock.

Each instruction was formatted to use 3 bits for the opcode and 12 bits for the address. There were 8x basic instructions and 3x extra instructions for a total of 11x instructions, as shown in Table 1.

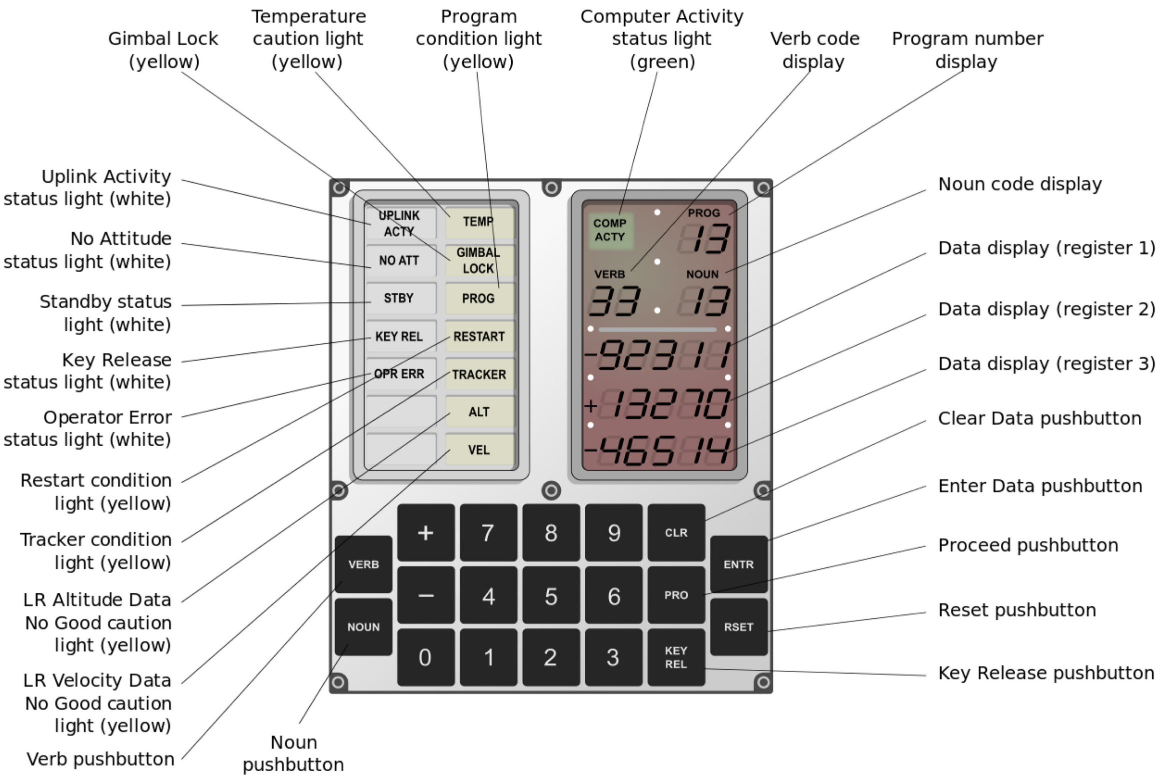

FIGURE 2. AGC DSKY interface.[5]

TABLE 2. Central registers of the AGC.

A	Accumulator
Z	Program counter
Q	The remainder from the DV instruction, and the return address after TC instructions
LP	The lower product after MP instructions

TABLE 3. Additional registers of the AGC.

S	12-bit memory address register, the lower portion of the memory address
Bank/ Fbank	4-bit ROM bank register, to select the 1-kiloword ROM bank when addressing in the fixed-switchable mode
Ebank	3-bit RAM bank register, to select the 256-word RAM bank when addressing in the erasable-switchable mode
Sbank	1-bit extension to Fbank, required because the last 4 kilowords of the 36-kiloword ROM was not reachable using Fbank alone
SQ	4-bit sequence register; the current instruction
G	16-bit memory buffer register, to hold data words moving to and from memory
X	Input to the adder or the increment to the program counter
Y	The other input to the adder
U	Output of the adder (1's complement sum of the contents of registers X and Y)
B	General-purpose buffer register, also used to prefetch the next instruction
C	1's complement of the B register
IN	Four 16-bit input registers
OUT	Five 16-bit output registers

The AGC had 4x 16-bit "central" registers, as shown in Table 2, for general computation and 13x additional registers, as shown in Table 3.

The AGC had a 16-bit word length using 15 data bits and 1 parity bit. It had 2,048 words of random access memory (RAM) using magnetic core memory and 36,864 words of read-only memory (ROM) using core rope memory; both had cycle times of 11.72 μs. A ROM module from the AGC is shown in Figure 3.

Memory was organized into 1-kiloword banks, the lowest bank was RAM and the remaining were ROM. Core rope memory is relatively simple, wires are passed through magnetic cores to indicate a 1 or bypass a magnetic core to indicate a 0. Since you can pass multiple wires through a single core, it made it trivial to increase memory density. At the time, a relatively large amount of memory could be stored in a relatively small volume—a whopping 72 KB/ft^3 (or 2.5 MB/m^3)! For comparison, the first 8-in floppy disk could hold 80 KB. The vast majority of the software written for the AGC was stored on the ROM. It was literally woven into the core rope memory by factory workers, which took several months to complete. The source code for the AGC has been open sourced and made available on GitHub by former NASA intern Chris Garry as of 2016[7]; it was originally made publicly available in 2003 by the Virtual AGC Project.

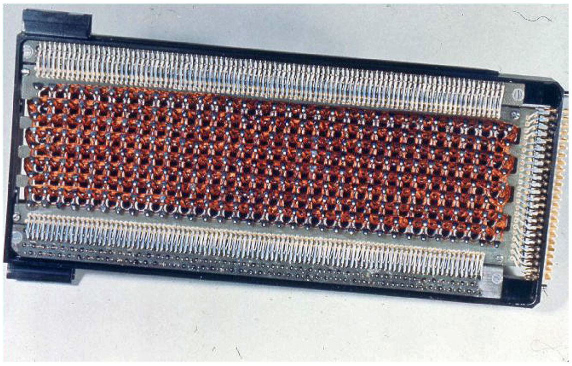

FIGURE 3. AGC core rope memory.[6]

CONCLUSION

The AGC is, in many ways, an engineering marvel. Given its success, it was later used to demonstrate the effectiveness of fly-by-wire systems, which replaced manual flight controls in airplanes with electronics ones. Think about it: the AGC was used to send human beings from planet Earth, through the Earth's atmosphere, into outer space, and onto the moon all before technology as simple as a floppy disk was available. Stop for a moment and appreciate that it is nothing short of extraordinary.

WE HAVE GONE FROM WEAVING LITERAL WIRES THROUGH MAGNETIC CORES TO PROCESS TECHNOLOGY SO ADVANCED THAT HUMAN BEINGS CANNOT EVEN PHYSICALLY TOUCH IT (IT IS ALL AUTOMATED AND COMPUTERIZED).

The use of silicon ICs has evolved rather substantially since the AGC. Taiwan Semiconductor Manufac-turing Company is already working on 3-nm process technology. We have gone from weaving literal wires through magnetic cores to process technology so advanced that human beings cannot even physically touch it (it is all automated and computerized). While I look forward to mankind's advancements in technology and space exploration, it is important to understand how far we have come and, in many ways, how far we still have to go.

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