PRESENTER: These test engineers are checking out a sophisticated collection of telescope, gyroscope, and electronics for Project Apollo. This guidance and navigation system will be mounted in an Apollo spacecraft to aid our three astronauts on their voyage to the moon and return. The miniaturized computer at the very heart of the system is our story today on *Science Reporter*

[MUSIC PLAYING]

FITCH: Hello, I'm John Fitch, MIT science reporter. Today, we're at the MIT Instrumentation Laboratory, which has been given design responsibility for this guidance and navigation system, which will direct our Apollo spacecraft on the way to the moon and back.

At one time, the direction of the rising sun, or perhaps the winding riverbed, was all that man needed in his restless search for new land. Centuries later, the quadrant of the magnetic compass guided his way, even across the open sea, even after familiar landmarks had long since disappeared.

Today, we speak of traversing a million miles of empty space, where there is no north nor south, no rising nor setting sun, not even any up or down. It's an extremely complicated task requiring many, many measurements and millions of calculations.

As you can see from this Apollo flight plan, there are several critical maneuvers that have to be performed. After the Apollo spacecraft reaches its Earth orbit, it must be injected into a translunar trajectory at just the right place in time and space. Someone has compared it to shooting at a moving target from a revolving platform, which is mounted on a train, which is going around a curve.

Then at the halfway point, long about here, the program course must be examined for errors, and possibly a midcourse correction made. There are many other similar maneuvers. And to learn about the guidance and navigation system which will make this possible, we talked with Mr. Eldon Hall, deputy associate director of the Instrumentation Lab.

HALL: The guidance and navigation system consists of two measurement elements-- the controls and the computer, and the computer display and controls. The inertial measurement unit, shown up here, but normally mounts in the back, consists of gyros and accelerometers that measure the angles and velocity of the spacecraft in this fashion. The spacecraft rotates, and the inertial measurement unit holds the reference so that angles can be measured.

The sextant is an instrument very similar to that used by the sailors to navigate on the surface of the Earth.

FITCH: What kind of a problem might you have to solve on your way to the moon?

HALL: The most basic problem is determine the position at any point in time. And that can be illustrated in these charts.

The sextant shown here represents the spacecraft. And to determine the position, an angle must be measured between a point on the Earth and a star. And you can see that, as you move away from the Earth, this angle would narrow down, thus giving the distance between the Earth and the spacecraft. The astronaut first positions the spacecraft so that a point on the Earth, a landmark, is visible through the sextant. Then he positions the sextant angle so that the star is superimposed upon this landmark.

FITCH: What kind of a landmark might he see?

HALL: This one is San Francisco Bay, as you can see here. However, the Great Lakes, or Cuba, or Cape Cod at the tip of Florida, any of these points make suitable landmarks.

FITCH: And then through some system of mirrors, you actually superimpose the star on [INAUDIBLE].

HALL: That's right. The mirror is inside the sextant-- will bring the star within the field of view, so that he can superimpose it on the landmark.

FITCH: How is this angle actually measured?

HALL: It's done automatically by the computer. The astronaut must first identify to the computer the star and the landmark he is planning to use. Then, as he's positioning the spacecraft and the sexton, the computer is measuring the angles between the two. When the astronaut is satisfied that the star has superimposed upon the landmark, he pushes the Mark button, telling the computer to record these angles and the time of the measurement. From that information, the computer can compute the position of the spacecraft in space.

FITCH: Now that you know the position, what can you do about it if it isn't right?

HALL: The computer can position the spacecraft, turn on the motors and steer it, and shut the motors off.

FITCH: Will you be coasting on a new and corrected path?

HALL: That's right.

PRESENTER: To see the Apollo guidance and navigation system in operation, we visited the Systems Test Laboratory and talked with Mr. Ramon Alonso, assistant director of the Instrumentation Laboratory.

ALONSO: One of the interesting aspects of the guidance system is the way in which the astronaut controls the guidance equipment through the computer. And he does so by means of the display and keyboard, which is a subsystem. There are two instances of the display and keyboard. One is with the rest of the navigation equipment in the lower equipment bay, and the other is near the couches where the astronauts can operate the computer without leaving their couches.

The system of codes used is reasonably simple. It consists of a numeric verb and a numerical noun.

FITCH: These are little sentences made a numbers then?

ALONSO: Essentially, if you strain a bit. An example of it might be a verb, 16, which is continuous display in decimal, and a noun, which is time. I picked these. I know it will work. I have now told the computer what I want, but I have not yet told it to go ahead and do what I want.

When I press Enter, the computer proceeds to display time. And it does so giving me times, from launch perhaps, in hours and hundreds of hours-- 98.56 hours from launch. And it also gives me a fine view of the lower part of the time in seconds and hundredths of seconds. That is useful occasionally.

FITCH: [INAUDIBLE] around launch time. That would be interesting.

ALONSO: The computer will continue to display that information until told otherwise. And it's told otherwise by another verb. In this case, the verb is terminate, 34. It's not forgotten that command.

Another example of the use of the computer might be to position the optics. That is something that can be done manually, and usually would be, but it affords us a good view as to how the computer is operated. The optics are now pointing in a certain direction, and I want to change the direction to another target. And I will invoke a verb, which is point, verb 41, and a noun, which is optics, noun 55.

FITCH: Point the telescope.

ALONSO: Point the telescope. When I press Enter, the computer then receives the request, the angle to which I wish the optics pointed.

FITCH: The numbers have changed, and they're flashing, aren't they?

ALONSO: That's right. The flashing indicates that action is requested of the operator. And the verb and nouns have changed to tell the operator what it is that is expected of him. Verb 21 is load the first component, the first angle, and noun 57, it used to be 55, is the angle. 55 was the telescope, and 57 is the angle which the telescope makes.

In this case, the angle I want is 180 degrees. And I enter that. And now, it asks for the second angle.

FITCH: Or 22 [INAUDIBLE].

ALONSO: The second angle is plus 325. Now when I press Enter, the camera, which will come close to the eyepiece, will see the telescope [? slew ?] and point to another target. As you can see, the crosshairs were lined up on the edge of the rightmost of the two targets, and the computer is now driving the optics telescope with relation to the spacecraft. And it's aligning it on the rightmost of this [INAUDIBLE]. There you can see the crosshairs right in the middle of the target.

Suppose now, that we have done the optical sighting by hand rather than by the computer and that we wanted to inform the computer that we are on target. This is part of the procedure that is done when star sights are made, as Mr. Eldon Hall mentioned previously.

That is done by means of a mark button, which is located in the lower equipment bay. When the telescope is on target, the astronaut presses the Mark button, and the computer changes the display to display, that's the verb, mark information, number 56. And what it displays are the two angles that the telescope is making and the time at which that measurement was made. Notice that these angles are very close to the ones that were commanded originally in our earlier efforts.

This information is part of what is necessary for the computer to then estimate the present position and velocity of the spacecraft, to estimate what the velocity correction is that ought to be [INAUDIBLE] and then to execute that velocity correction.

PRESENTER: To learn more about the remarkable little computer at the heart of the guidance and navigation system, we talked with Mr. Albert Hopkins, assistant director of the Instrumentation Laboratory.

HOPKINS: This computer is similar to its round-based big brothers that are dominating our lives so much today. And that is, fundamentally, a high-speed adding machine with the additional features of having a memory into which it can write results and from which it can take data, very much as an accountant has his ledger. And it also-- it has a self-contained list of instructions analogous to an accountant's training, so that this tells the computer what to do in sequence.

If we look over here, I can show you more about how the computer operates. The adding machine of this computer is a high-speed arithmetic unit which carries out the fundamental arithmetic processes. All of the complex operations we've seen today can be broken down into long lists of arithmetic. The arithmetic unit receives its data from a memory divided into two sections, and it puts its results back into the erasable portion of that memory. This is the portion which is similar to the accountant's ledger.

FITCH: What is the fixed memory?

HOPKINS: The fixed memory is unique to the space age. It is a memory which cannot be written into by the arithmetic unit, and it contains information which must last the entire mission. It's here for safety. This contains--

FITCH: The location of stars and things you wouldn't want to forget.

HOPKINS: That's right. This contains a list of instructions, which are fed one at a time to the sequence generator, which generates all of the controls necessary to operate the entire computer.

Input data, which comes from the angle measuring devices that we saw earlier or the keyboard, comes in through input conditioning circuits and is available in the erasable memory. The arithmetic unit can operate upon this input data and compute results designed to be output. These results are placed in a particular portion of the erasable memory, where they are sent through output conditioning circuits out to other instruments which need this data, such as, for instance, the displays or perhaps a rocket motor.

FITCH: When you say this computer is very much like land-based computers-- and yet, I think of them as occupying bays of equipment. And you've got all of this squeezed into a little box. How did you do that?

HOPKINS: Miniaturizing a computer like this requires a judicious choice among many quantities. It's first necessary to minimize the number of circuits which you use. It's necessary to minimize the size of the components which you use, and it's necessary to package them as tightly as possible.

This must not be carried too far. If it's carried too far, it can endanger the reliability of the computer, so that a compromise must be sought.

FITCH: What kinds of circuits are involved?

HOPKINS: In the memory, and also in the power supplies and the input-output of the computer, conventional components are used, with the exception of the fixed memory, a piece of which we see here. This fixed memory is actually composed of magnetic cords with wires woven in and out, sewn in with a pattern, where the information here is in the pattern of the sewing. The remainder of the computer, the arithmetic unit, the sequence generator, the so-called connective tissue--

The logic section, so-called, of the computer is made up of a single type of unit. This is a micro circuit gate. 4,300 of these are used in the computer to make up this the entire segment. These are packaged together tightly. They fit in a fairly small space and are interconnected in separate modules in one side of the computer.

PRESENTER: The Apollo computers are manufactured by the Raytheon company in Waltham, Massachusetts. The computer itself consists of two trays, one containing Logic Modules, the other, memory modules. To learn how these modules are put together, we talked with Mr. Jack Poundstone, Raytheon's Apollo engineering manager.

POUNDSTONE: In this room, John, we run all of the electrical components through a screening and burn-in process. You know, there are over 30,000 parts that go together to make this machine.

Every part is put through an electrical test and then a series of environmental stresses. As an example, this girl is placing the micrologic units into a fixture that will be used in this centrifuge. Here, the fixture is spun at a very high speed, and 20,000 Gs of force is placed on each component.

FITCH: That's a lot more than it will ever experience, isn't it?

POUNDSTONE: Yes, that's true. But we put more forces on, more stresses than we really expect, to ensure the high reliability.

FITCH: So this is really sort of a torture chamber in here.

POUNDSTONE: That's right. In addition, we run all the parts through a leak test to make sure there's no leaks in the can. The part is put into a high-pressure helium tank, and if there is a leak, the helium will be forced into the can. Then we put it in a vacuum chamber and evacuate and test for the amount of helium coming out.

FITCH: I see.

POUNDSTONE: In the final phase of the screening and burn-in process, the girl puts the parts, as she's doing here, into a test socket. Then those parts are placed on this burn-in rack. Here, they will be operated for almost a week at a over voltage stressed condition.

FITCH: You actually are operating them?

POUNDSTONE: Yes, we're operating the parts. Any failure, or any significant failures of any our tests is cause for rejection of the entire lot of 5,000 parts. After we've ensured that we have good components, then we want to make a module.

Now, the little cans here are placed in these holes in a component holder. Then we take a matrix, which is a complex wiring pattern-- it's placed on the back, and the wires are folded over and welded to the leads of the micrologic unit itself.

I'd like to show you now how we make a matrix. Here, we see an operator who is placing a piece of mylar insulator that has adhesive on both sides, and this insulator has previously had a pattern of holes punched onto it. This is placed on this longitudinal wire winder. As the piece advanced, strips of nickel ribbon are laid down in a longitudinal direction on the mylar.

Next, it's taken to the vertical wire winder. Here, the operator is placing it on the machine, and as the drum rotates, wires are laid down on the opposite side of the mylar in a vertical direction. The wires will be laying down right over the areas where the holes have been punched.

FITCH: Some running one way on one side, and others running the other way on the other side.

POUNDSTONE: That's right, John. The next operation is to perform the welding. This is done on a automatic welding machine. This machine-- we are advancing the matrix underneath these weld heads. And whenever a hole appears under a weld head, the weld is commanded to drop and perform a weld, and this makes a feedthrough connection from one side of the insulator to the other.

In the final operation, this girl uses of cutting tool to remove the excess pieces of wire to give us the final configuration of our precise wiring pattern.

FITCH: This matrix then is the wiring that sort of connects one little microelectronics circuit to another.

POUNDSTONE: That's right, John. This wiring diagram shows you how the matrix can be used to interconnect micrologic elements. See here, a wire will run from this can down here where it's woven through to the other side, run down, break out to another can, and up here to another. After that operation, the operator can now take the matrix, fold it, and cement it to a component holder. Then the little micrologic elements themselves will be placed in the holes, and we're ready to bend the wires down and make a weld.

After completing that operation, the entire assembly is then put into this metal header. This header contains-- provides the structure for the assembly, and it has a row of metal pins here. And the leads to the matrix will be welded to the pins.

FITCH: So that one logic stick can be connected to another one.

POUNDSTONE: That's right. Let's take a look at how the operators do this operation in detail. This operator is loading the little micrologic elements into the component holder. Note that she takes each one and dips it in a little adhesive before she puts it into the holder.

FITCH: I see, so it's really fastened in place,

POUNDSTONE: That's right, John. Now, she's ready to weld the wires to the leads coming out of the can.

FITCH: So you don't solder them? You actually weld these-- .

POUNDSTONE: We weld it. She takes her little pair of tweezers and properly aligns the wire to the tin of the can. When the alignment is right, she then makes the weld. That little flash you saw there was when the weld was actually made. After that matrix welding is completed, she's ready to place the assembly into the header.

FITCH: So it actually does fit in that little space.

POUNDSTONE: Yes, she very gently forces it in. And she's ready now to weld the matrix wires onto the pins of the header. Upon completion of that operation, we now have an electrically completed module.

A test man will now take this module and run an electrical test. He plugs the module into a special test socket, and then this special piece of equipment will electrically energize all of the circuits to ensure that they are properly working. The information for the test is stored on a piece of paper tape.

FITCH: After this testing then, this logic stick is ready for the computer?

POUNDSTONE: No, there's one more stage, John, and that's the potting of the module.

FITCH: What do you mean by potting?

POUNDSTONE: The potting is this plastic coating that provides a covering for the wiring and the components. Now, the module is ready to be plugged into the logic tray assembly.

FITCH: That's number 38. And there are all these other modules too. They might be a little different.

POUNDSTONE: That's right.

FITCH: What about the memory modules?

POUNDSTONE: The memory modules of the computer are made using a basic component, which is a donut shaped magnetic core. This core will be placed into a component holder, like so. After the component holder has been completely loaded with cores, we're then ready to do the wiring.

In order to perform the wiring operation, we store about 20 feet of wire in this needle, see how that wire comes out of there? Now, the operator will take the core holder and pass the needle through the core, around to the other side, and then weave it back through in a different position. Let's watch how the girls do this operation in a little more detail.

Here, we have a pair of girls who are wiring the address wiring of the core [? rope ?] module. They pass the wire back and forth stored in the needle and put it through the cores in a particular wiring pattern. Each time the wire goes through, they must very carefully wrap the wire around one of those little nylon pins. And you can see, what that does is pull the wire away from the center of the core to allow room to pass the needle through again.

FITCH: I see. These address wires go to every single core?

POUNDSTONE: That's right. When the wire is completely weaved into the rope, it must be terminated on a little solder terminal. The girl strips the insulation from the wire and very carefully wraps it around the pin. Then they use a magnifying glass to inspect their work.

The sense wiring information, or the wiring that contains the program of the fixed memory, is performed by using this machine. The machine indexes to a particular location of a core, and the girl passes the needle through the aperture and provides the wire to go through the right core.

FITCH: She doesn't have to think about which core it goes through next?

POUNDSTONE: No, the machine does that for her. Note, each time the wire passes through, that little aperture jogs down and pulls the wire around one of the nylon pins. When she passes the needle through, she will trip the switch with the needle, which causes a tape reader to advance-- there's the tape reader-- and that, in turn, causes the [INAUDIBLE] to move its position.

After all the wiring is completed, these nylon pins that we used to temporarily hold the wire can now be removed. Next, we must press the wires very gently down into place, so we'll be able to fold up the whole assembly. Now this operator is folding the core planes into a sandwich-type construction and laying them into the header of the module.

Now, we're ready for electrical test. We must ensure that every wire in every component are properly located. And the operator puts the module into this piece of special test equipment, and a program stored on paper tape is then used to exercise the module.

FITCH: But this is certainly a complicated looking maze of wiring in here.

POUNDSTONE: That certainly is, John. That module contains 512 cores and over a half a mile of wire. And it performs the function of storing over 65,000 individual pieces of information.

FITCH: You put that potting compound all over this too?

POUNDSTONE: Yes. In the final form. here's the module [INAUDIBLE], and it's all ready to be plugged into the memory tray assembly.

FITCH: How do you connect one module to the next one of these trays?

POUNDSTONE: That's done on the back side of the tray. Let me show you.

FITCH: Oh, I see.

POUNDSTONE: Here you see a fairly complex wiring pattern. We're able to interconnect from module to module by running wires from this pin to, say, that pin. Now, this pattern is so complex that we've used a computer program to determine the exact layout of each wire. That is, we may run a wire from here to here by going down this way, and over here, and up there.

FITCH: Why is that?

POUNDSTONE: Well, that's to avoid a density problem where the wires could buildup if we lay them all in the same channel.

FITCH: I see. But actually, I think that would make it rather hard for somebody who was trying to wire from one pin to another to remember all that.

POUNDSTONE: That's true. In fact, the wiring is so complex that a human being just can't do it. So we use a machine to do all of this wiring.

This is the automatic wire-wrap machine. The operator has placed the tray in the machine and is starting the wiring operation. Now, this machine has two wire-wrap tools that can be incremented to the proper location on the tray. When it's found the right pins, the wire is stretched out and formed in the right pattern, then the insulation is stripped from the ends of the wires, and finally, the two tools drop down and wrap two pins simultaneously.

Now, in order--

FITCH: Can it go around corners, and things?

POUNDSTONE: Yes, you can. And in order to run the wire in a different direction, sometimes the tray is rotated. It can be positioned in four different locations. The information to command those wire-wrap tools is contained on these IBM cards. Each card has the information for a single wire.

FITCH: How is the wire actually fastened to the pin, is it solder or welded?

POUNDSTONE: No, this is what's known as a wire-wrap connection. The soft copper wire is very tightly wrapped around the pin. And you might see that the pin is a square-cornered pin. And in this fashion, the wire digs into the sharp corners of the pin and provides a good electrical connection.

Now, we're entering the computer system test area, John. After the trays have been potted, and modules assemble to the trays, we bring the machine into this area and run through exhaustive temperature tests and vibration tests.

And finally, we perform a complete electrical check out of the computer. This piece of equipment is the computer test set. This provides the means to enter data into the machine and monitor all of the various outputs. Here we have a piece of equipment that provides the power and interconnects the computer to the two displaying keyboards.

FITCH: What kind of test would you perform on it?

POUNDSTONE: Actually, we've written a very special fixed-memory program that allows the machine to test itself. As an example, we can have the machine test that all of the possible displays have been created. Let me show you. As I enter that, you see that the displays go from all nines, to all eights, and so forth down the line.

FITCH: Is this the last time that the computer is tested before it actually is flown?

POUNDSTONE: No, the computer will be tested several times as part of the guidance and navigation system. In fact, the same type of equipment that we have here will be used for these various tests.

FITCH: Thank you very much, Mr. Poundstone.

Today, we visited the Instrumentation Laboratory at MIT, and the Raytheon company in Waltham, Massachusetts. I'm John Fitch, MIT science reporter.

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