The Mechanical Analog Computers of Hannibal Ford and William Newell

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The history of mechanical analog computers is described from ear/y developments to their peak in World War II and to their obsolescence in the 1950s. The chief importance of most of these computers was their contribution to the superb gunnery of the US Navy. The work of Hannibal Ford, William Newell, and the Ford Instrument Co. is the framework around which this account is based.

For over 40 years mechanical analog computers provided the US Navy with the world's most advanced and capable fire-control systems for aiming large naval guns and setting fuze times on the shells for destroying either surface or air targets. A large part of this preeminence can be attributed to the work of Hannibal Ford and William Newell. However, the credit has usually been withheld. first because of security classifications and later by the resulting widespread ignorance of even the main facts of their stories.

The history of the evolution of fire-control equipment can be divided into three crudely defined periods of progress: early. middle. and late, being respectively the eighteenth, nineteenth, and twentieth centuries. In the early period, the eighteenth century. there was no perception of fire control as a hierarchical system. so there were no inventions on the *system level.* Lack of concern for improvement caused continuation of the status quo. In the middle period, the nineteenth century. there began a trend toward automation in many practical pursuits (e.g., the cotton gin. railroads. steamboats. and glass-forming machines) which extended to naval gunnery. Handwheels provided a mechanical advantage in training and elevating guns. The man-machine system was being made easier and better for the men by delegating more to machines.

In the late period, the twentieth century. people have seen the system as a whole, and they have been conscious of missing subsystems. Inventions then took place on the top echelon, and system engineering began to deal with the entire hierarchical system. In the late period there was concern for errors of system performance. In the case of a fire-control system, the contributions of all causes to the ultimate miss data were studied to identify the most critical remaining sources of error.

Early analog computing mechanisms

To understand the types of mechanisms invented by Ford and Newell, it is necessary to briefly examine a few of the simple components from which they arose. The history of mechanical analog devices goes back at least to Vitruvius (SO BC), who described the use of a wheel for measuring arc length along a curve. the most simple integral in space. Many other elementary analog devices were described before the modern period: Differential gears (Figure 1). used for adding or subtracting two variables. arc usually ascribed to Leonardo da Vinci: and Leibniz is credited for the idea late in the seventeenth century of a similar-triangles device for equation solving or root solving.'

The first device to form the integral under a curve, or the area within a closed curve, was the integrator of B.H. Hermann in 1814. Hermann's integrator was essentially a wheel pressed against a disk. as shown in Figure 2. There was a second disk over the first. which squeezed the wheel between them. The rate of rotation of the wheel is proportional to the product of the disk rotation rate and the radial location of the point of contact of the wheel on the disk. That is, the rate of change of angular position of the wheel z is given by

$$\frac{dz}{dt} = Ky\frac{dx}{dt}$$

where z is the time integral of y times a constant. x is the angular position of the disk, and K is a scale constant. Note that the variables in this device are angular and linear positions.

An early application of such integrators was the integration of force over distance to measure work. Another application was a planimeter to measure the area within a closed curve. In fact. the chief impetus behind the early integrator inventions of the nineteenth century was to get an improved planimeter.

James Clerk Maxwell' described a ball type of integrating device while he was an undergraduate: it was incorporated in a planimeter design. In about 1863. James Thomson' conceived an equivalent integrator in which a ball rotates between the disk and a cylinder (see Figure 3). The angular position of the cylinder is the output variable z. and the ball replaces the wheel of the Hermann integrator. The ball is held in a housing that is translated along the radius of the disk with displacement y. This integrator became the heart of numerous harmonic analyzers and time analyzers.

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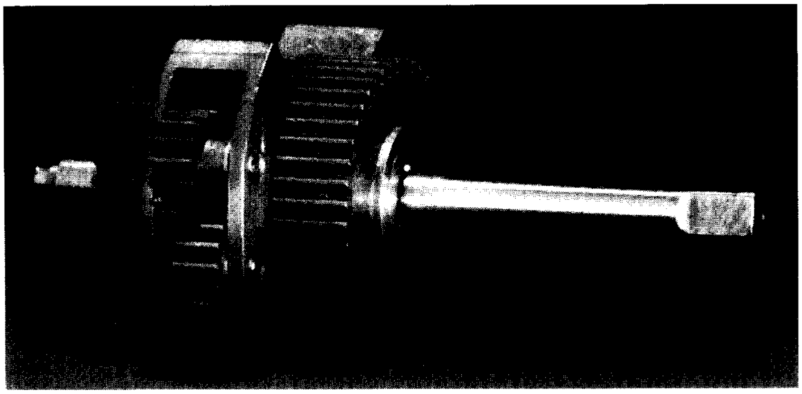

Figure 1. The Ford 3/8-inch spur differential gears. (Photograph by Laurie Minor, Smithsonian Institution.)

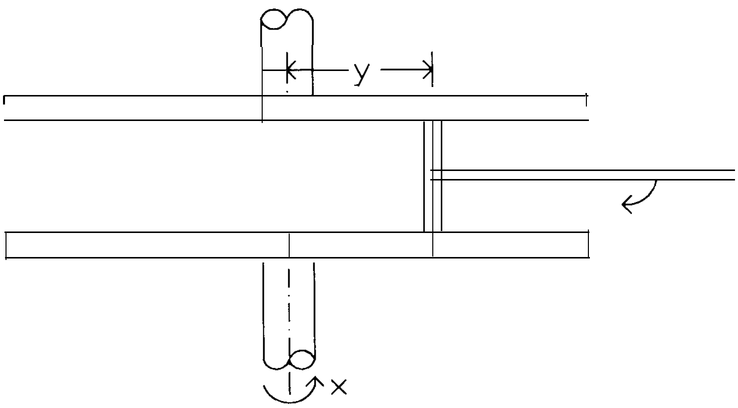

Figure 2. The Hermann integrator.

A two-dimensional cam (Figure 5) was used to generate a virtually arbitrary function of one variable: The input is the rotation angle of the cam, and the output is the radius of the cam at the point of contact of a roller. A three-dimensional cam (Figure 6) was similarly used to generate a function of two variables. such as time of flight as a function of range angle and elevation angle to the target.

William Thomson. Lord Kelvin, had the powerful idea of using analog computing mechanisms tied together to solve a differential equation.[6] Ten years later, Abdank-Abakanowicz built an "integraph," which had the purpose of solving one particular differential equation. Thomson's idea was the conception of differential analyzers. which. however. did not become a practical reality until the 1930s with the work of V. Bush.' Lord Kelvin also invented a pulley device for solving simultaneous equations.[8] Larger versions were built by MIT professor Bohn Wilbur in 1934 and 1935. An "isograph" was developed at Bell Telephone Laboratories. following a concept due to Thornton Fry in 1937. It could find the roots of polynomials of up to 10th degree, even if the roots were complex numbers. It was based on a Scotch yoke mechanism to transform from polar to rectilinear coordinates.' The state of the art of these and other computing mechanisms has been summarized as of the end of World War II by Macon Fry" and Clymer.[10]

These analog mechanisms. together with a "multiplier" (using slides and based on the mathematics of similar triangles) and a "resolver" (which produced $R \sin \phi$ and $R \cos \phi$ from R and ϕ by means of a Scotch yoke mechanism). were among the building blocks for the practical computing systems to be described.

In 1881 a different type of integrator was developed in Madrid by V. Ventosa.[4] It consisted of a tiltable drive roller. a ball, and four output rollers. If wind velocity is put into the drive roller (marked "A" in Figure 4) as angular velocity. and if wind direction is put in as tilt angle. then the four output rollers turn with speeds proportional to the compass components of wind velocity. As a computing device this ball constitutes a "component integrator" -it produces the time integral of the sine and cosine components of a given varying magnitude. Later forms of trigonometric integrators were developed by Hele-Shaw, Smith. Newell (see Appendix), and others.

Harmonic analyzers were developed to determine the coefficients of a Fourier series to fit a given record. such as tide data. Lord Kelvin built two. the second in 1879. A refined version by Michelson and Stratton built in 1897 could sum 80 Fourier terms. According to Vannevar Bush" a three-dimensional cam for multiplying was developed by Bollée.

Naval surface fire-control computers of 1910 to 1930

It is necessary to describe a little of the technology of naval gunnery and fire control to present a snapshot of the state of affairs just before the entry of Hannibal Ford into the picture. What he accomplished was in direct response to the needs of the US Navy. He was responsible for the development of mechanical analog computers of unprecedented size. complexity, dependability. ruggedness, and accuracy. The mechanical analog computers of 1915 were, however. quite simple, small, and uncomplicated compared with their descendants in the next three decades.

The fire-control problem. In the nineteenth century the fire-control problem greatly increased in difficulty. Ranges had been 20 to 50 yards in *1800.'* [1] Most of the engagement between the Monitor and the Merrimac had been fought at 100 yards. which was virtually point-blank range, and the ships were slow in maneuvers, affording gunners plenty of time to take aim." By the end of the century, naval guns could fire at ranges far in excess of 10,000 yards. Ships could move much faster, and still rolled and pitched to large angles in heavy seas, causing both sights and guns to move off target.

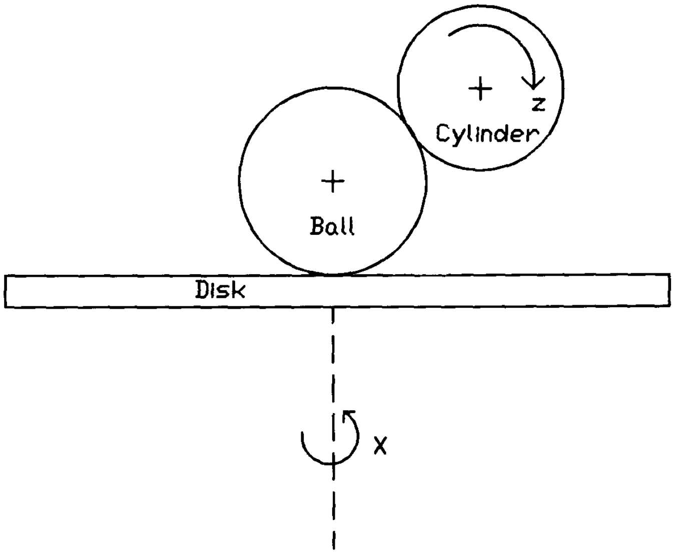

Figure 3. The Thomson integrator. (The displacement is perpendicular to the paper away from the disk center.)

With the increased ranges available to guns the problem of "spotting" the errors in the locations of splashes of shells became more difficult even in the clearest weather. Likewise. the task of determining target range became more challenging. With the increased target range went a more than linear increase in the time of flight of a shell. so the target had more time in which to maneuver. Moreover. the greater time spent by a shell in flight enabled wind to have very important effects upon the impact point. Another complication was that rifling the gun barrels. while reducing random scatter. caused a systematic lateral "drift" of the projectile. which had to be compensated for in aiming the guns.

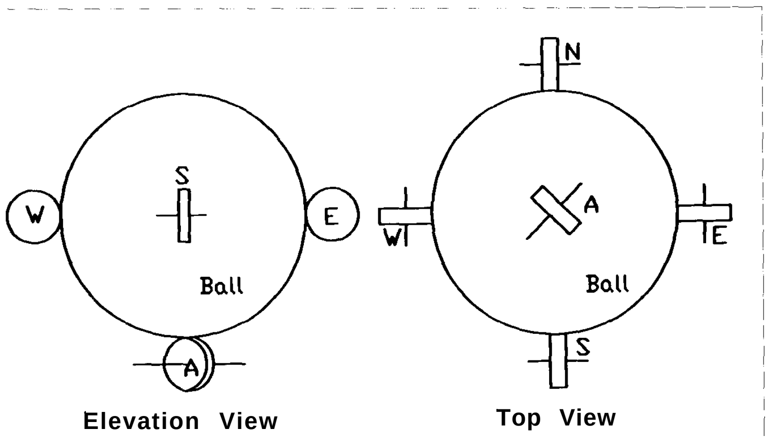

Figure 4. The Ventosa integrator.

The greater need for angular accuracy at greater ranges increased the importance of some relatively minor effects, such as variationsin atmospheric temperature and pressure. barrel erosion resulting from previous firing (which reduced the initial velocity and hence the range of the shell). propellant weight and temperature variations. projectile weight. and so on.[12] The largest disturbances to accurate naval gunnery were the rates of change of range and target bearing due to relative motions of "own ship" (the firing ship) and the target.

Clearly the crisis in naval gunnery created pressure to improve naval fire-control equipment.

Fire-control equipment of 1910 to 1915. During World War I fire-control equipment included three classes of devices.[13]

Devices aloft. Spotters' scopes were used for viewing splashes in order to phone gun angle corrections ("spots") relative to the line of sight. Optical range finders of successively improved types determined range to the target. (American models had a base of 18 to 20 feet. but the British had only 9 feet. giving double the error. German range

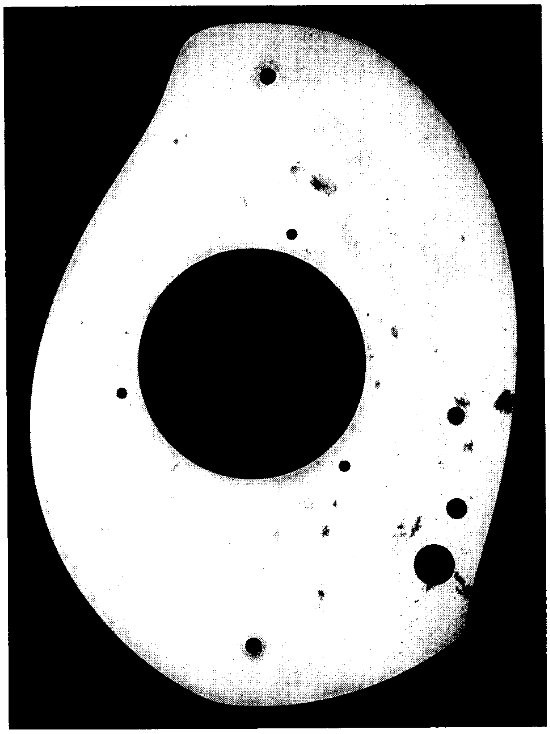

Figure 5. A two-dimensional cam. (Photograph by Laurie Minor, Smithsonian Institution.)

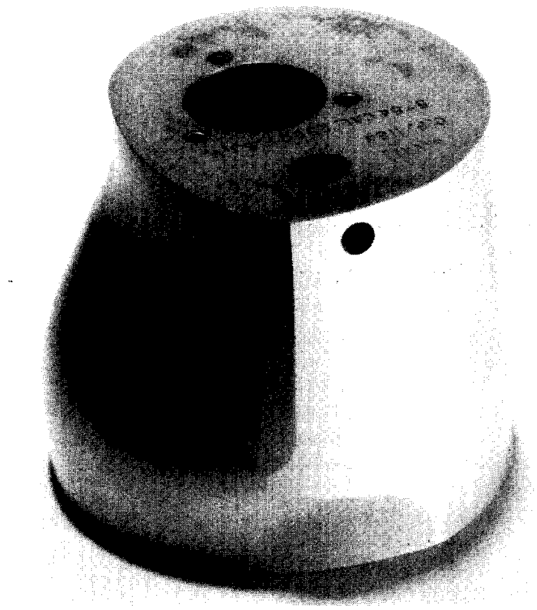

Figure 6. A three-dimensional cam. (Photograph by Laurie Minor, Smithsonian Institution.)

finders were the best because they had the best optics and thus the best view.)

Directors. after about 1912.” consisted of sights kept aimed at the target in train and elevation in order to correct gun train and elevation angles for own ship roll and pitch. The English company Vickers had the lead in director development.” The US Navy purchased some of these directors from Vickers for 5-inch guns.

Devices belowships (in the "plotting room" or “control information center”). Gyrocompasses determined own ship course (purchased from the Sperry Corporation by the US Navy after 1910). Plotting boards were **used** for plotting the paths of own ship and target to determine range at the future time when the projectile would arrive (“advance range”), using range-finder data. The invention of the plotting board is ascribed to a junior gunnery officer in about 1906.

Range clocks let operators set in the present rate of change of range to obtain a crude running estimate of range. “Time of flight clocks” told the time when a shell fired “now” would reach the target. The Argo clock was a mechanical analog computer for solving the relative motion equations for range. As of 1912. the US Navy had a "fire-control table” (a mechanical analog computer) having input from the range finder and director.

The pitometer log measured own ship speed.

Devices at the guns. Mechanical drives for guns appeared between 1907 and 1910. Manual tracking of command angles on dials positioned guns in train and elevation.[12] Graduated sights on the guns had been used at the time of the American Civil War but were obsolete by 1910 or 1915.

Differences between Britain and the US. The connectivity of the primitive fire-control “system” composed of the foregoing fragments foreshadowed some aspects of modern fire control. However. there were differences among the systems used by different countries. For example, between Britain and the US, there were differences in who controlled gunfire, from where. and with what use of the plotting room.” In the US Navy, the plotting room personnel controlled the fire, using data from spotters and their own data to compute gun angles. On the other hand, the British preferred optical system angular outputs. Director personnel controlled the fire. using the plotting room information mainly to correct range.

Thus the stage was set for the contributions of Hannibal Ford.

The fire-control computers of Hannibal C. Ford

Hannibal Choate Ford was born in Dryden, N.Y., on May 8.1887. His parents were Abram Millard Ford (born February 22. 1831) and Susan Agusta Giles Ford (born June 3, 1834).

As a young boy. Ford showed mechanical talent with clocks and watches. Between high school and college he

Figure 7. Hannibal C. Ford and his engineering staff about 1922. Ford is front and center; the others are unknown. (Photograph from the Sperry Gyroscope collection.)

worked at the Crandall Typewriter Company, Groton, N.Y. (1894). at the Daugherty Typewriter Company, Kittanning, Pa. (1896-1898), and at the Westinghouse Electric and Manufacturing Company (1898).

He studied mechanical engineering at Cornell University, graduating in 1903 as a “mechanical engineer in electrical engineering.” Evidently his classmates at Cornell respected his mechanical inventive ability, because his motto in their senior yearbook was, “I would construct a machine to do any old thing in any old way.” He was elected to membership in Sigma Xi, the honorary society for research.

After graduation Ford worked for the J.G. White Company. New York (1903-1905), where he developed and held two basic patents issued in 1906 on the speed-control system long used in the New York subways. At the Smith-Premier Typewriter Company, Syracuse, N.Y. (1905-1909), he developed over 60 mechanisms of commercial importance and received a number of patents over the period 1908 to 1915.”

In 1909, Ford worked for Elmer A. Sperry. whom he had known as a young man in his home town, Sperry having been somewhat older. Ford assisted Sperry in the development of the gyrocompass, a mechanical device for determining own ship’s heading. The following year, Ford was promoted to be chief engineer of the newly formed Sperry Gyroscope Company, a position which he held until 1915.[15]

In 1915. Ford resigned from Sperry to organize his own company, the Ford Marine Appliance Corporation, which became the Ford Instrument Company in 1916 (see Figure 7). The company’s mission was to develop and sell fire-control systems to the US Navy. Its first product, Range Keeper Mark 1, was introduced into the US Navy in 1917 on the USS Texas.

Ford’s Range Keeper Mark 1 (abbreviated Mk. 1) performed a remarkable number of continuous functions in real time for a computing system in those days:

1. It generated range rate.
2. By integration of range rate it determined present range.
3. It generated the relative speed at right angles to the line of sight” but not the present target bearing angle.‘”

The rates were obtained by resolving own ship's and target's speed vectors along, and perpendicular to, the present line of sight. These operations required mechanical resolvers, differential gears, and an integrator.

Ford's integrator (Figure 8) was of superior design for achieving high accuracy and long life. It used two stacked balls, held by stiff springs, between a disk and cylinder, each made of hard steel. The balls were held in place by pairs of small rollers in a carriage. This design permitted the carriage to move even when the disk was not moving, a feature that was necessary when integrating with respect to a variable other than time. The author does not know if Ford was aware of the prior art, such as James Thomson's integrator and William Thomson's (Lord Kelvin's) computer concept,[6] before applying for his patent.'"

Own ship speed (measured from a pitometer log) and estimated target speed and course, own ship course (from a gyrocompass), as well as target bearing, were entered manually with the aid of dials, hand cranks. and knobs. The assembly of mechanisms was driven by an electric motor whose rotations represented the elapse of time. Present range, from the range finder, was telephoned to the plotting room, where the range keeper was kept.

Meanwhile, Arthur H. Pollen, a British inventor, had devised a mechanism of the differential analyzer type (called an "Argo clock") to solve, on a continuous real-time basis, the relative motion equations for own ship and a target ship: "It accounted in large part for the extraordinarily good shooting of several Russian battleships during World War I."'" It was used also in the British Navy. Pollen's invention must have preceded, by a short time, Ford's range keeper.

During World War I, the US Navy obtained the patent for the British Pollen fire-control computer system (Argo clock), and the Range Keeper Mark 1 was modified to incorporate one of Pollen's concepts (dividing by the range and integrating with respect to time to get the bearing angle). By dividing relative motion across the line of sight by present range, the Ford range keeper (called appreciatively the "Baby Ford") was able to generate the rate of change of target bearing and integrate it to get the target bearing angle, which in turn defined the line of sight. Thus the range and direction to the target could be generated and known, even if the target was lost from sight for a while. These modifications introduced another integrator and a divider into the evolving range keeper.[13]

Another of the early additions to the Baby Ford was a ballisticcapability." It was to determine the time of flight of the shell to the predicted point of impact, the bearing of that point, and the range of that point. Then the gun angles could be calculated to implement that prediction. The guns were steered by hand (following pointers), but they were powered by Waterbury Speed Gears (hydraulic drives).

Another capability was "rate control." This function enabled determining corrections to target speed and course as a result of data obtained from spotters aloft regarding the splash locations relative to the target. The Baby Ford had a rudimentary scheme for doing this, but it required the prediction calculations to be stopped while rate control was being done. Hannibal Ford earned a patent for his rate control scheme.

By the end of World War I, the Ford range keepers provided a serviceable nucleus for a partially mechanized fire-control system. It was roughly comparable with the British system. The British gun directors were deemed better than those of the US Navy, but British range finders, having a smaller baseline, were inferior in accuracy. The Pollen Argo clock and Baby Ford were about a standoff." Acceptance of the Baby Ford was not universal and immediate. Some senior fleet officers tended **to** resist it, preferring the plotting boards, where they could "see" the situation at a glance.

In addition to developing range keepers, Hannibal Ford almost single-handedly developed an entire gun director. It included an optical turret, a stable element to establish the vertical on a rolling and pitching ship, an angle gyro pointing at the target, and the associated Baby Ford range keeper, which included a ballistic computer.

Naval fire control from 1930 to 1950

In the 1920s the international clamor for disarmament forced the US Naval budget to a very low point. Although the situation improved in the 1930s, when the US Navy began again to grow, money was still tight. The Bureau of Ordnance was forced to drastically limit what it could procure. A striking example is offered by the deck tilt corrector that was, in the 1930s, ordered by the bureau to be developed by Ford Instrument Co. Unfortunately, there was only enough money to order half of the desired corrector. During part of that period Ford Instrument Co. was down to a three-day week for its employees.

In the late 1920s, Hannibal Ford began developing the first antiaircraft (AA) fire-control system, including both a director (Mark 19) and a range keeper. Because of the target's ability to maneuver at high speeds and angular rates as seen from own ship, the AA fire-control problem was intrinsically much more challenging than was fire control for a surface target. Despite the work on AA fire control, systems for surface fire control continued to pour from the Ford Instrument Co. under Ford's technical direction. For example, the company developed the Range Keeper Mark 8, which was used in the Marks 24, 31, 34, and 38 Gun Directors. Equations and a schematic diagram of information flow in the Range Keeper Mark 8 have been published in the open literature, although values of constants in the equations were not given."."

The period starting in 1930 saw the introduction of many improvements in fire-control systems. One was automation of data input into the computer. Friedman'" provides the following list of data entered manually in 1933 range keepers:

Variable	**Source**
Range	Phoned from range finder
Own ship course	Gyrocompass repeater
Own ship speed	Pitometer log
Target course	Initial estimates for rate control
Target speed	Initial estimates for rate control
Target bearing	Automatically from director
Spotting data	Spotter, by telephone

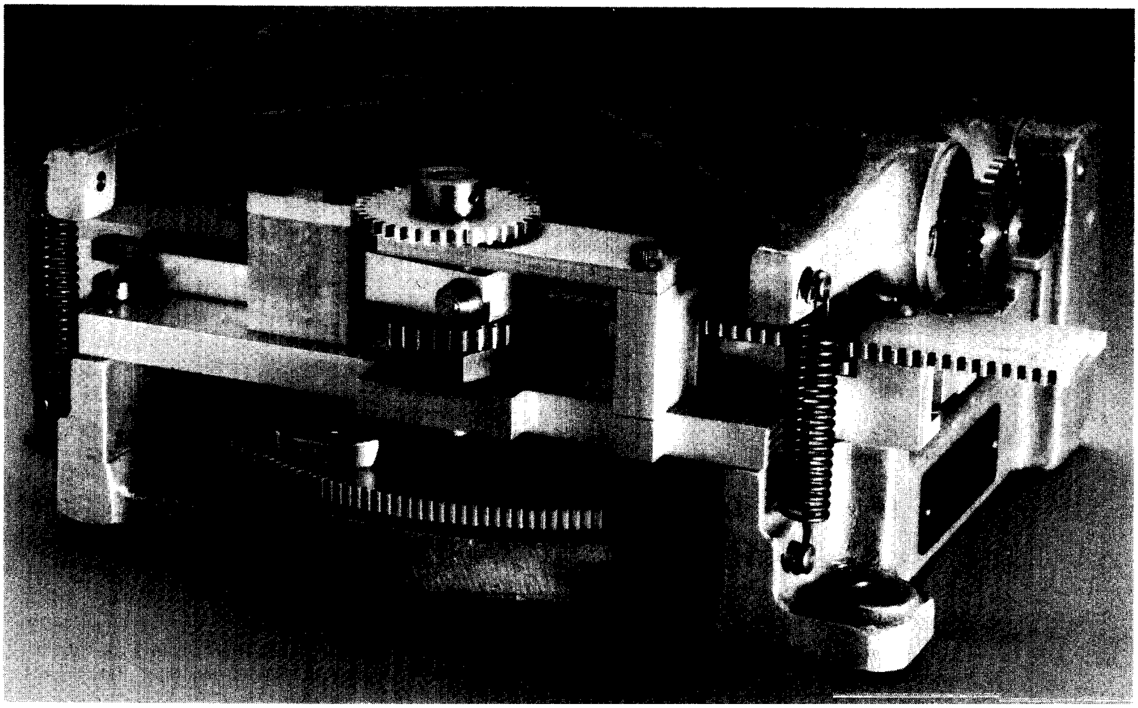

Figure 8. Hannibal Ford's integrator. (Photograph by Laurie Minor, Smithsonian Institution.)

By the late **1930s the input of these variables was much more highly automated.**

The Gun Director Mark 33 was initiated in 1932 for dual-purpose 5-inch/38 guns on ships of all sizes. It resembled an apple on a stick when it was mounted aloft, and it had vibration problems. It was used with the Ford Range Keeper Mark 10 for antiaircraft fire, and it had a stable element and a computer below deck. A total of nearly 850 Mark 33s was eventually installed.

A typical World War II range keeper or computer consisted of three sections:

1. Tracking section (the original range keeper functions dealing with relative and absolute motions of own ship and target).
2. Prediction section (predicting range and time of flight, each from two moving time origins: the time of gun firing and the time of fuze time setting; and the required gun angles found by considering the ballistic functions and wind).
3. Correction section (calculating and applying corrections due to own ship angular motions. namely. roll and pitch. requiring trunnion tilt and deck tilt corrections to the gun angles).

By the time of World War II most main battery fire control was done by Range Keepers Mark 8 in Directors Mark 34, mainly for cruisers, and Directors Mark 38, for cruisers and battleships.[12] The Ford range keepers were superseded by the Ford Computer Mark 1 in the Gun Director Mark 37. This director was first tested in 1939 and it quickly became the standard dual-purpose director in World War II, although many Range Keepers Mark 10 in Directors Mark 33 also were built and used. The Bureau of Ordnance considered the Computer Mark 1 to be "enormously successful."" The system included transmission of data to and from the computer below decks by means of synchros. Designed originally for the 5-inch/38 guns, it was soon modified by Ford Instrument Co. for a number of other guns and ammunition types as well.

Choice of the term "computer" in preference to "range keeper" recognized the growing inadequacy of the term "range keeper" to describe the system. Keeping range was a small part of its function.

Fine as this fire-control equipment was for 5-inch guns and up, it was not suited to the smaller guns and decentralized control that proved necessary in World War II for defense against incoming aircraft in large numbers. Moreover, the large fire-control systems were not economically feasible for use on small naval vessels and merchant ships having guns even as large as 3 inches. Fire control for close-in attack by a number of aircraft was "sadly neglected in the years between the two wars" due to an "ill-founded complacency" concerning the ability of fire-control systems

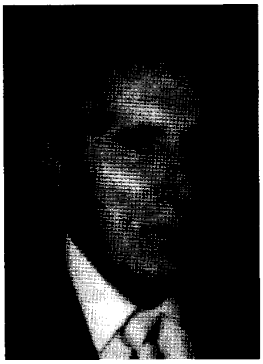

Figure 9. William H. Newell in 1988.

of the day to destroy all targets at greater ranges.'* The Japanese exploited this weakness with several distinct modes of attack.

Ford Instrument Co. was caught up in the rush by the Bureau of Ordnance to develop fire-control systems to meet these new needs. Ford developed, to various extents, the Gun Directors Mark 45, 48, and 49 — all intended for close-in AA fire with small guns. The Mark 49 used a gyro to determine lead angles based on the precession rates measured in tracking the target. It was ready by late 1942, and nearly 350 were eventually delivered.

Ford's answer to the merchant ship problem was the Computer Mark 6 -used with Gun Directors Mark 52 and 53. Although only about the size of a large wheel of cheese, it ingeniously contained a simplified capability for solving the surface fire-control problem.

In spite of all these developments with gyros, reticules, and lead computers, they only partly replaced the old open sight in World War II. Gunnery and fire-control system designers had prepared for a different enemy — one more like a towed target remaining at a distance of miles.'

Optical range finders gave way to radar in the late 1930s and early 1940s. This resulted in a substantial increase of capability of searching for targets (with "broad-beam search radars") and tracking targets (with "narrow-beam fire-control radar"). No longer was it necessary to illuminate a target with star shells at night or lose a target in mist. Moreover, the range, target bearing, and elevation signals were cleaner, smoother. and more accurate. The measurement of range and target direction angles had been freed from the limitations of the human operator of an optical range finder. The advancement of synchros for transmitting and receiving data in fire-control systems was a step away from manual follow-the-pointer systems. These synchro systems are described in Department of Ordnance and Gunnery publications."

A few problems existed because the Bureau of Ordnance had to deal with other bureaus in getting its equipment installed. For many years — until 1943, in fact — the gun mount foundations provided by the Bureau of Ships did not meet specifications of the Bureau of Ordnance.'* Presumably the accuracy of gunnery then improved somewhat.

One of the most valuable advances was the development (about 1940) of powerful control systems for automatic training and elevating of guns of all sizes. After the installation of automatic control, the guns could fire with precise aiming at any time, freeing gunnery from the centuries-long dependence on synchronizing firing with rolling of the ship. Although the earliest systems were susceptible to oscillations and lags.' improvements in the mathematical design of control systems, and (according to William Hampton, then a Ford employee) the use of steel piping for greater hydraulic stiffness, resulted in satisfactory performance.

Another advance, the "proximity fuze," made it possible to avoid having to set fuze time and incurring the associated errors of burst time. Projectiles could be loaded directly and fired immediately, and this allowed gunnery accuracy to improve even further.

The entire functional environment of fire-control computers had to evolve to keep pace with the increased sophistication of the other components.

Evolution on the system engineering level

A respectably mature discipline of system engineering had developed in naval fire control by the late 1930s and, from that time on, the days of the inventor left to his own judgment were gone.

One evidence of system engineering was the standard set of symbols that came to be used in equations to designate variables, such as Tf for time of flight and R2 for advance range. Likewise, there was a standardized vocabulary of concepts such as "advance range" (the range at time of predicted impact) and "time of flight" (the time from firing to impact). As more and more corrections were incorporated in the range keepers, even the equations took an increasingly standard form which was then imposed by the Navy across all manufacturers. Some of these equations are given by Friedman[13] and the 1941 US Navy Academy book."

Another evidence of the use of system engineering is the top-down generation of specifications, beginning with the Bureau of Ordnance, with the manufacturers going into greater detail in the specifications. This procedure resulted in the systematic production of schematic diagrams, engineering drawings. training manuals, and other documentation.

Another hallmark of system engineering was the analysis of system performance errors: For each Ford Instrument Co. product there was calculated a full complement of "class B errors." These were the deviations of the system's answers from theoretical answers calculated from the exact equations for specified cases. Analysis of these errors led to knowledge of where more accurate calculations were needed in the product. The next step was to develop an "error budget" that allocated allowable errors among all contributing categories in a hierarchy. The error budget pointed to novel developments needed as well as to limits on errors of conventional equipment.

Yet another aspect of system engineering was the analysis of errors of the enemy's system, seeking weaknesses to exploit. By whatever means were used. the Japanese identified opportunities for dive bombers, torpedo planes, toss bombers, kamikazes, and so on. These tactical weapons presented the ships' fire-control systems with short-range, high-range rate, and/or high bearing and elevation rates, where the accuracy of the Gun Directors Mark 33 and 37 fell off sharply.'* That low performance is in contrast to the reported high accuracy with slow targets, even at great ranges. (For example, the battleship Washington is said to have achieved nine hits on the Japanese battleship Kirishima, out of 75 rounds of 16-inch shells at 19,000 yards range in the night battle of Guadalcanal in 1942, where radar was used.)

Table 1. Differences between differential analyzers and fire-control computers.

Characteristic	Differential analyzers	Fire-control computers
Application	Solution of arbitrary differential equations sets (general-purpose computer)	Computing continuous aiming and fuzing of naval guns
Environment	On "solid ground" in a building	In a moving warship experiencing severe shocks and vibrations
Construction	Originally spread out on a large breadboard for flexibility	Designed into minimum volume for shipboard use
Design style	Laboratory instrument design practice	Rugged, yet precise machine design
Problem size	Several differential and algebraic epuations	Many differential and algebraic equations

The contributions of William H. Newell

In 1926 the Ford Instrument Co., which was then working on its first antiaircraft director, got a new employee: William H. Newell, aged 16. He worked first in the shop making high-precision mechanical computing components and, a year later, transferred to the Test Department where he acquired the techniques of making mechanical analog computers perform to their limits. In the evenings for seven years he went to the College of the City of New York to study engineering. He advanced rapidly as a result of his nearly unique talents as an inventor, designer, and developer of mechanisms and indeed, like Hannibal Ford, entire computing systems. In 1943. at age 32, he became chief engineer.

Newell's **inventions.** Newell (see Figure 9) has received 80 patents in connection with his work. The subject matter was long classified, so the public has not known of his contributions. Any attempt to determine Newell's accomplishments by concentrating on patent dates is difficult because the date of filing for a patent might have been much earlier than the date of issue due to secrecy orders preventing responsive issue.

Among Newell's mechanical. hydraulic. and electrical inventions (see Appendix) were 31 devices of fundamental importance to analog technology. Included are devices such as a hydraulic computer: an irreversible drive involving wedges to lock two disks if direction starts to reverse, as in back torque from gun recoil: a torpedo director (Mark 2); a director for defense against horizontal bombing runs; a scheme for using trains of balls, with wheels and steering rollers, to integrate complicated trigonometric functions and solve the fire-control tracking problem; and a computing device for predicting the deck angles of an aircraft carrier at the instant an airplane would be landing.

Many of these inventions concerned ways to deal with inertia and friction loads on the driving mechanisms. They were essentially servos, then usually called "follow-ups." that provided torque amplification while following a shaft angular position signal. These servos had a differential gear for comparing the output angle of the servo with the input signal angle, producing an error angle, which determined the signal to the drive to reduce the error-that differential gear was represented on schematics by a cross in a circle. a symbol which is still used on schematic diagrams for the error-determining subtraction in control systems of many types today.

The Ford Instrument equipment often used an "intermittent drive," a device that enabled one part of the equipment to drive another over only a limited part of its total travel. Ford had designed the first intermittent drive, but Newell improved the design, putting the whole drive on one shaft.

The significance of Newell's work. One of the hallmarks of Newell's work has been that he took extra trouble to find the neat and simple way to do things, rather than go ahead with his first idea. A notable testimony to Newell's and Ford Instrument's skills was that Wernher von Braun selected them to build the mechanical and gyro guidance system for the first Redstone missile. Ford Instrument Co. built also the guidance system for the Jupiter missile.

Newell's work was done with originality and self-reliance. One might wonder if he got ideas from other organizations in those days of technical ferment. However, Newell has denied that he got ideas from MIT's differential analyzers or Servo Lab work: In fact. MIT bought Ford components, and Newell believed that Ford Instrument was "ahead." According to Newell. Bell Telephone Laboratories, the Naval Research Laboratory, the Office of Naval Research, the ENIAC project, and the university researchers, including such avid communicators as John von Neumann, Harold Hazen, Jay Forrester, Claude Shannon, Norbert Wiener, Warren Weaver, and Vannevar Bush, had no effect upon his work.

From 1965 to 1977, Newell worked for Perkin-Elmer, in Norwalk, Conn.. on challenging projects such as the space telescope, first on the senior technical staff and then as a consultant. But that is another story worth telling.

Other mechanical analog computers

At this point in the story, attention is turned from fire control to other specialized applications of mechanical analog computers. The author makes no attempt to describe the type generally known as a "differential analyzer" because it is already adequately described in other places -except to distinguish it from the computers used in fire control. Differential analyzers differed dramatically from fire-control computers. as shown in Table 1.

These were the two distinct species that represented the high point of mechanical analog computer development, each in its own way. Williams' felt that *'the analog tradition reached its height in the differential analyzers." This author disagrees that either species was superior.

Torpedo mechanical computers. Torpedo data computers for use by submarines were developed by the Arma Corporation in 1935. Arma had been building stable elements and other gyroscope instrumentation for weapons since its founding in about 1920. The torpedo data computer automated much of the process of inserting data into a torpedo to establish its course, speed, and depth. It was primarily a mechanical computer with some electrical components. By World War II most submarines in the US Navy had a TDC Mark 3.[12] A simpler and more compact version of the torpedo data computer, the Mark 2, was developed by William Newell (see item 5 in the Appendix).

Destroyers of that period carried Torpedo Director Mark 27, which contained a mechanical computer. A number of approximations could be made, because the resulting errors could be ignored when torpedoes were fired in a spread. As a result, the equations were much less complex than those of the antiaircraft fire-control problem.[12] As early as 1942, the Bureau of Ordnance conceived of a need for a system for computing and displaying the data of concern in antisubmarine warfare. The resulting product was the Attack Director Mark 2, which contained a mechanical computer. Fifteen were delivered."

In the early 1950s, Arma built a mechanical analog computer ("coordinate conversion computer") containing a gimbal system. Designed at MIT, it was one unit of a fire-control system for use by the Navy in the Korean War. The torpedo itself contained several small mechanical analog computers. They were extremely delicate and complex, with the result that their effectiveness was reduced. These computers included the following mechanical devices:

1. The course control system that activated a rudder.
2. A computer to determine the course angle for collision with the target.
3. A depth-control system, relying on a diaphragm to measure depth (water pressure) and a pendulum to measure rate of change of depth. The pendulum was later replaced by a gyroscope to avoid the error due to longitudinal acceleration. The change was Newell's idea." (See item 25 in the Appendix.)

Bombsight mechanical analog computers. Another highly specialized type of mechanical analog computer was developed for use in bombers. Bombsights were remarkable for their extremely small size and high precision. The Norden bombsights contained over 2.000 parts. Development began at the end of World War I and progress was rapid: The Bombsight Mark 3 was contracted for in 1922. the Mark 11 was accepted in 1931, and the Mark 15 was being tested in 1931." Bombsights were also made by Sperry.

One of the refinements to bombsights was the invention by Newell and Lawrence Brown that enabled a bomber to navigate by some identified visible point, when the target itself was obscured, and yet still bomb the target.

Sights and directors for small guns. Major naval vessels had no small guns until after Pearl Harbor, when the large numbers of incoming aircraft had overwhelmed the fire-control systems for large guns. As a result, a rapid evolution had to take place to provide something better than the open sight mounted on the gun barrel, which had been standard armament against aircraft in World War I.

A significant advance was made by the lead-computing sight developed in the 1930s by Charles S. Draper of MIT. Draper's sight evolved from his earlier products of an aircraft instrument to display rates of turn and his tank gun sight. These devices used precessing-rate gyros mounted on the line of sight to the target, Each rate was multiplied by a suitable factor to produce a proportional lead angle, which was applied to the gun direction." The overall precision was on the order of 2 percent. The Navy learned of the Draper sight belatedly: One was tested in July 1941, and the sights entered service in the fall of 1942 — built by Sperry and by Crosley. Eventually 85,000 of the Gun Sights Mark 14 were bought for naval vessels.

The US Navy's response to the need also included the development of some heavy machine-gun directors. Contracts for development were awarded to Ford Instrument for the Gun Director Mark 45, to General Electric for the Mark 46, and to Arma for the Mark 47 (the Mark 46 and 47 never reached production). The Mark 45 was completed as early as 1942: however, it was too complicated and heavy as a computer, and it was too crowded as a workplace, so production of it was stopped. It was replaced by the Gun Director Mark 49, which also was being developed by Ford Instrument. The Mark 49 contained a gyro torqued hydraulically to precess it, and it had hydraulic pick-offs. The Mark 49 was replaced by the Mark 51.[12] Located on a pedestal remote from the guns, it used a Draper sight to transmit train and elevation angle orders to heavy machine guns. It was manufactured by Sperry Gyroscope Co., beginning in January 1942.[12] Its performance was poorest for surface targets, which had small angular rates as seen by the sight.

Gun Director Mark 56 was designed at MIT. It utilized an unusual mechanical analog computer technology: four-bar linkages. By properly proportioning the bar lengths, one could design linkages to generate a surprising variety of functions. Some of the linkage computers were made by Ford Instrument Co. Vannevar Bush, in his role as one of the organizers of the National Defense Research Committee. was able to do much for small gunfire-control developments. and he had a hand in its production.

In addition to the naval gun sights and directors mentioned here for heavy machine guns. comparable or smaller systems were developed for use in aircraft, such as the largest bombers (B-29). There was. for example, a Mark 18 Turret Gun Sight. which had a computing mechanism. It was followed by the Mark 23 in 1945.[12]

Other analog mechanical computers. Flight simulators for pilot training have been in existence since the "Pilot Maker," alias "Blue Box," of Ed Link, developed in 1929.[18] Link's flight simulator contained a pneumatic analog computer that used principles he had learned in his father's organ factory. A mechanical analog flight simulator was designed and built by Ford Instrument Co. in 1945. Later flight simulators were based on electric and electronic analog and then digital technology. Mechanical analog computers were used also in early guidance systems for missiles: Arma did the inertial guidance for the Atlas missile. William Newell also invented a guidance system that worked without gimbals, integrating components of acceleration and velocity to determine present position (see item 27 in the Appendix).

The range of the German V2 rocket was determined by a mechanical analog computing device. It integrated acceleration twice to get distance traveled; it also contained some linkages and differential gears to relate the twice-integrated acceleration to horizontal distance." As the technology was refined, new applications were undertaken. Most of these and other mechanical analog computers were eventually superseded by electrical analog computers.

The descendants of mechanical analog computers

Mechanical analog computing evolved in two directions, branching into developments in AC analog computers and DC analog computers.

AC analog developments. In about 1940 the market for tools for performing mathematical operations was quite small. Mechanical desk calculators served acceptably for all but the largest problems, such as fire control and exterior ballistics. When Thornton C. Fry wrote a survey article'" about the extent of the use of mathematics in industry, he had little to report outside the telephone and aircraft industries. One could not then imagine the explosion of electrical and electronic technologies that would result in a flood of computers available at modest cost.

The principles of AC (alternating current) electrical analog circuits had been known since Steinmetz in the 1880s. Currents entering a node were known to add. The charge on a capacitor was known to be the time integral of the current that had flowed through it. It was known that a servo-driven potentiometer could be "tapped" to yield a function or a product of two variables. This technology was not developed, however, until Bell Telephone Laboratories found application for it in a developmental gun director early in World War II.

The BTL project was to develop an AC analog gun director, the T-15. It was funded in November 1941, and the model was completed a year later and tested in December 1942." The T-15 was never put into production: it was, however. used for research with targets flying trajectories that were not straight lines.

The T-15 led to a proposal to the Navy, in February 1942, to construct an AC analog version of the Ford Instrument Company's Computer Mark 1. A contract was awarded in September 1942 for development of this "Mark 8 Computer." Although it proved to be faster than the Computer Mark 1 in completing the initial transient of acquiring and locking onto a target, the Mark 8 Computer was never produced. It had one other feature worth noting: a special electrical integrator that was developed for it.

A refinement to bombsights invented by Newell and Lawrence Brown enabled a bomber to navigate by a visible point, when the target itself was obscured, and yet still bomb the target.

Ford Instrument Co., under the direction of Harry McKenny and William Newell, developed an AC analog computer, the Mark 47, which replaced the mechanical analog Computer Mark 1.

From 1945 to 1950 the Dynamic Analysis and Control Laboratory at MIT developed an AC analog computer, using 400-cycle AC components in a guided missile flight simulator. This was an activity within Project Meteor. The flight table was mounted on four concentric gimbals so driven as to avoid gimbal lock under all conditions.

DC analog developments. DC (direct current) amplifiers had been used since the post-World War I days of radio. They were highly developed in the 1930s by BTL, which used them for signal amplification in telephony. They were used also by George Philbrick at Foxboro, as early as 1937 or 1938, for simulation of linear processes and control systems." Developments of amplifiers for use in simulation were made also by John Ragazzini et al. at Columbia University in about 1940. Bell Telephone Laboratories devoted itself to the development of DC vacuum tube amplifiers for use in analog computers for fire control after about June 1940. A patent. applied for in May 1941, was issued in June 1946 as US patent 2404387 to C.A. Lovell, D.B. Parkinson, and B.T. Weber. Their contemplated systems used summing networks, potentiometer cards for functions, and an integrator using an amplifier and a capacitor.[21]

In November 1940 Western Electric received a contract to develop a model of a DC analog gun director, the T-10. It was to use the BTL-developed DC analog technology. The model was tested successfully in December 1941.[21]

The success of the T-10 led to a contract to build the production version, the M-9 Gun Director. It was delivered in December 1942, and it was placed in service in early 1943. It was used during the V1 "buzz bomb" attack on London to control the fire of 90-mm guns located along the English coast. During the month of August it shot down 90 percent of the buzz bombs that arrived, and in its best week it shot down 89 of the 91 that arrived. The M-9 (see Figures 10 and 11) was aided by radar and proximity fuzes.[21] A British version of the M-9 (the T-24. directing 4.5-inch AA guns) had its prototype completed by May 1942.[21]

Figure 10. M-9 gun director in action. The tracking unit with its two operators is in the foreground, while the computing units are in the truck.

Another offspring of the M-9 was the "M-8 Gun Data Computer," which BTL developed for the US Coast Artillery Board for control of 6- to 8-inch guns firing at surface targets. The M-8 corrected for the parallax angles of different guns firing at the same target and also corrected for the earth's curvature. It was never used in combat, because there were no targets for it.[23]

Lest it be gathered that all electronic analog developments in World War II were made by Bell Telephone Laboratories, note that the Arma Corporation developed, starting in the summer of 1940, an electronic analog antiaircraft computer for the Mark 47 Gun Director. It was to control 40-mm machine guns, but in 1941 it was changed to the 3-inch gun and was to be incorporated in the Mark 50 director. Deliveries of 43 units began in May 1943, but the computer had some serious difficulties: It weighed too much, and it was too complex for feasible mass production and for ease of maintenance. The system was further complicated by the fact that the electronic ballistic converter and fuze order computer had to control 40-mm. 1.1-inch, 3-inch/50, and 5-inch/38 guns.[12]

The promise of BTL's early electronic analog gun directors encouraged other computer developments in World War II. One, the AN/APA-44, was a bombing and navigation computer for aircraft. BTL also developed electronic analog flight simulators for pilot training for the PBM-3 Martin Mariner patrol bomber, the Grumman Hellcat fighter, and the Consolidated Privateer patrol bomber.[24]

After World War II, Project Cyclone was established to develop a DC analog computer for general-purpose applications. The work was done by the Reeves Instrument Corporation. Very soon there were competitive commercial products available from Electronic Associates, Inc., Applied Dynamics, Inc., and eventually about 30 more companies. These "analog computers" became the tools of choice for a generation of control system designers, missile and aircraft designers. and analytical engineers in all branches of engineering for purposes of dynamic and often real-time simulation. These developments left the AC analog computers far behind in accuracy and other performance features. One of the key steps was chopper-stabilization of the DC amplifiers, which otherwise had a maddening drift.

One of the people who worked almost anonymously behind the scenes in this period was Perry Crawford at the Naval Special Devices Division. He had a hand in the advanced thinking underlying Project Cyclone. He also had some influence upon the course of Project Whirlwind, an early digital computer developed at MIT which is best remembered for its magnetic core memory by Jay Forrester. Crawford had written two provocative theses at MIT,[25,26] which contributed to the frontier thinking of the time toward electrical digital computers.'

The defeat of mechanical analog computers

The beginning of the end for mechanical analog computers as the computers of choice in fire-control systems began just before World War II. They were then at their zenith. No competition was in sight. yet the computers that would replace them in less than a decade were already in development.

Mechanical analog computers for fire control were much in demand as a result of the rapid growth of the US Navy in those days. Accordingly, the Bureau of Ordnance was anxious that Ford Instrument Co. might not be able to manufacture them fast enough to meet the **need.** There were critical skills, machine tools. and materials that were in short supply, any one of which could have produced a fatal bottleneck. It was only prudent that the Bureau of Ordnance then sought alternatives on a second-source-of-supply basis.[21]

The government's expenditures for electrical and electronic analog computers for fire control and aircraft simulation have been mentioned. This flow of money sufficed to fund the necessary research and development. The suddenness of the emergence of electrical and electronic analog computers is easily attributable to the equally sudden awareness of a need.

It seems plausible that the lack of such funding and procurement desire in the previous years was responsible for the relative stagnation of electrical and electronic analogs. This stagnation existed in spite of the almost-ready availability of virtually all of the required electrical and electronic analog components. One of the reasons for the stagnation is that the mechanical analog people believed firmly that no electronic computer could survive the onslaught of the shipboard shock and vibrations in battle upon vulnerable vacuum tubes and solder joints. Probably this thinking also kept electrical components, except the sturdy servos and synchros, out of mechanical analog computers.

No one had realized the cost in battle due to the sluggishness of even the fastest mechanical computers in converging upon a target. This discovery was not made until speedier electrical analog competitors were developed and demonstrated. However, once discovered, this feature of the electrical analogs proved to be essential in dealing with a multiplicity of very fast aircraft and missiles as targets.

Another reason for the lack of effort to develop electrical analog computers until just before World War II was that the required parts (resistors, potentiometers, and capacitors) lacked sufficient precision for fire control. The necessary precision was, however, developed when the need materialized.

During World War 11 the electrical analogs were on the scene and were being rapidly developed with funds diverted from mechanical analogs. Moreover, with production came cost reductions for electrical analog which could not be matched by the precision mechanical computers. Similarly the size and weight of electrical analog computers came down rapidly to be more than competitive. The scales were tipping in favor of the electrical analogs. By the time they tipped all the way, it had been a sudden process over only a few years. The shift of contracts to electrical analog computer manufacturers and the general reduction in level of postwar spending crippled the manufacturers of mechanical analog computers.

Mechanical analog technology died back but has not, even yet, died out. It is still in use where precise mechanical results are required, such as in very large telescopes, printing presses, and movable antennas. Mechanical analog technology survives also in many more subtle ways. For example, the "schematic diagrams" of mechanical analog computers evolved into "analog diagrams" for DC electronic analog computer problems or systems (in general- or special-purpose computers, respectively). Similar diagrams are often used in control engineering, digital computer simulation technology, and Forrester's "system dynamics." The present trend toward massive parallelism in digital computers also will continue the need for the analog type of diagram well into the future.

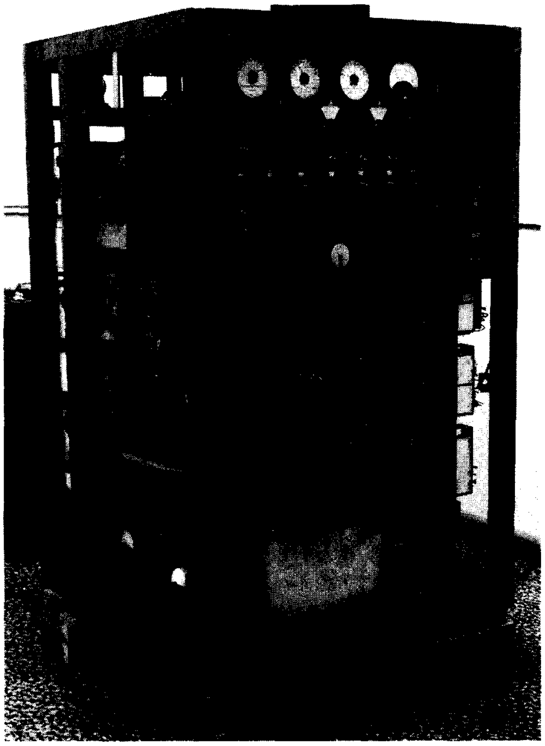

Figure 11. M-9 gun director (covers off).

The short reign of electrical analog computers

While the AC and DC analog computers were replacing mechanical analog computers. their own eventual successors — the digital computers -were appearing and growing in capability. Since that story is well documented in the *Annals of the History of Computing,* it is not repeated here. Suffice it to say that electrical and electronic analogs had a much shorter reign than mechanical analogs. From Ford's Range Keeper Mark 1 to the virtual stoppage of production of mechanical analog computers in the 1950s there was a reign of about 40 years. The electrical and electronic analogs, however, reigned supreme only about 10 years before they were surpassed and replaced by digital technology.

A large measure of the historical importance of mechanical analog computers stems from their service in naval fire-control systems from World War I to somewhat beyond World War II. Much of the credit for US naval fire-control systems stems from the design and performance of the Ford Instrument Company's mechanical analog computer products, including developments from Range Keeper Mark 1 to Computer Mark 1. These computers were superbly accurate despite their need to be rugged under the abuse of shocks and vibration in battle.

The outstanding inventors and developers of the Ford Instrument computers were Hannibal C. Ford and William Newell. Their technical leadership, which spanned four decades, provided a unique corporate capability.

Ford and Newell deserve to be recognized as mechanical geniuses at least on a par with Vannevar Bush. Bush has become the better known by far, because of his differential analyzers, because of his writings, and because of his visibility as an administrator on the national level. In contrast, Ford and Newell worked exclusively on classified projects unknown to the public, modestly wrote nothing, and were administrators only within the company. They let their inventions and developments speak for them.

It is unfortunate that the story of Ford and Newell has not been known and appreciated among engineers and the general public. The US Navy has had the facts all along, but it could not speak for many years because of the need for secrecy. The material could not be declassified until it no longer had current military importance. As a result, only those who were involved in the work have been privy to much of the story.

Likewise, in the author's opinion. mechanical analog computers for naval fire control deserve a featured place in the history of computing, as differential analyzers have enjoyed.

The outlook for future mechanical analog technology is confined to some highly specialized opportunities where its advantages outweigh its disadvantages. These opportunities are most likely to arise for one or two components rather than complete computers. The glory lies in the past.

Thus, the story of mechanical analog computers deserves a place in the history of computers. It is truly important in its own right and, in addition, the technology served as an early stepping stone toward today's digital computers. ■

Acknowledgments

The author has endeavored to portray the mechanical analog aspects of the history of computing from the perspective of a mathematical engineer. The author has been guided by correspondence with Hunter Dupree, a professional historian of science and technology. Michael Williams gets the credit for converting a long and disorganized paper into the form published here and then shepherding it through the editorial process. The author could not have structured, condensed, and enlivened it so well unaided.

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A. Ben Clymer is a retired consulting engineer who had been in a private practice specializing in simulation and simulators. His interest in mechanical analog computers stems from his employment at Ford Instrument Co. from 1942 to 1945. As a junior design engineer. he designed mechanical analog computers used in naval fire-control systems for S-inch guns and up and an aircraft flight simulator.

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Appendix

Among Newell's mechanical. hydraulic. and electrical inventions were the following:

1. A hydraulic computer. plus some hydraulic components, such as a device to generate a hydraulic pressure proportional to a displacement, and a hydraulic torquer and pick-off for a gyro in a gun director. Patents 2317293. Apr. 20, 1943: 2405052, July 30, 1946: 2483980, Oct. 4. 1949: 25 13888, July 4, 1950: 2533306. Dec. 12. 1950: 2550712, May 1, 1951; 2569571. Oct. 2. 1951: 2766587, Oct. 16, 1956.
2. Various rotary damping and/or inertia devices to be attached to a servo shaft to smooth the mechanical output with a low-pass filter. One of these, called a '*k-motor," acted only when the signal got rough, Patent 2400775.
3. Poitras and Tear of Ford Instrument developed an arrangement making a follow-up motor's speed proportional to error. thereby obtaining an exponential characteristic. making it a 'velocity-lag servo." This used a drag cup and gave an error proportional to velocity. To eliminate this error there was introduced a differential gear between the motor and drag cup with an inertia on the other differential input. which gave a smaller error proportional to acceleration. but no error proportional to velocity. Newell. in one application. used an air dashpot to obtain the velocity-lag servo effect.
4. An irreversible drive involving wedges to lock two disks if direction starts to reverse. as in back torque from gun recoil. This device prevents stick-slip oscillation when driving an inertia. whereas an "irreversible" worm drive does not stop stick-slip. Patents 2266237, Dec. 16.1941; 2402073. June 11, 1946.
5. A torpedo director (Mark 2). Newell simplified the mathematical basis. which enabled the size of the computer to be cut in half. Six of these systems saw service in World War II. Patent 2403542. July 9, 1946.
6. A director for defense against horizontal bombing runs. By restricting its applicability. Newell was able to do it with a much simpler computer than was in use. Patents 2403543. July 9, 1946; 2403544. July 9, 1946.
7. A combination of a coarse and fine synchro, using a cam-driven link to switch between coarse and fine. The patent application was filed in 1934, but the work had been done before that. Patent 2405045, July 30. 1946.
8. A single-ball integrator with a rack to eliminate tangent function effect. Patent 2412468. Dec. 10. 1046.
9. A scheme to prevent large inertial load on a hydraulic servo from overshooting. which involved introducing a spurious signal to start slowing it down before it reached the intended position. This was particularly important in synchronizing S-inch guns and in bringing heavier guns to a loading position. Patents 2427154. Sept. 9.1947: 2840992, July 1, 1958.
10. A triangle mechanism to generate the square root of the sum of the squares of two input position variables. Patent 2438818. Mar. 30. 1948.
11. A scheme for using trains of balls, with wheels and steering rollers. to integrate complicated trigonometric functions and solve the fire-control tracking

problem (related to the earlier fundamental work of Maxwell, Ventosa. Hele-Shaw. and Smith)."' Patent 2528284. Oct. 3 1, 1950.

12. An electrical servo (with Henry F. McKenny). Patents 2448387, Aug. 31, 1948; 2546271, Mar. 21, 1951.
13. A printing press registration scheme using a photocell (with McKenny). Patent 2576529. Nov. 27, 195 1.
14. An electronic analog resolver — given a magnitude R and an angle A. it computes the components R sin A and R cos A continuously while compensating for the magnetic distortion of the R input. Patent 2646218, July 21. 1953.
15. A "rate control" system whereby splash- or burst-point error data generated by a spotter topside would cause automatic continuous computation of corrections to target course and speed (patented in the name of Ford et al.). Ford had developed a rate control system that reversed the computation and found target course and speed, but in doing so interrupted the generation of the prediction problem. Newell used component integrators to generate corrections to the target course and speed from the spotting corrections without interrupting the continuity of the fire-control solution. Friedman gives the equations." Patent 2702667, Feb. 22. 1955.
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18. A mechanical integrator with reduced friction surface area. Patent 2693709, Nov. 9, 1954.
19. An "error reducer" unit for reducing greatly the pointing errors of main battery guns (developed in about 1950). Patents 2763988. Sept. 25, 1956: 2800769. July 30, 1957.
20. An electrical device containing tapped potentiometers for generating a class of functions of three variables. Patent 2817478. Dec. 24. 1957.
21. A computing device for predicting the deck angles of an aircraft carrier at the instant an airplane would be landing. Patents 2817479, Dec. 24.1957: 2888195. May 26, 1959; 2888203, May 26.1959: 2978177. Apr. 4, 1961: 2996706. Aug. 15, 1961; 3174030. Mar. 16. 1965.
22. A parachute-release device. with Howard Brevoort. Patent 2834083, May 13. 1958.
23. A device for squaring using a cone and cylinders (with S. Rappaport). Patent 2854854. Oct. 7. 19%.
24. A computing module for correcting for the tilt of gun trunnions. Patents 2902212. Sept. I. 1959: 2920817. Jan. 12, 1960; 1967663. Jan. IO. 1961.
25. A depth control for torpedoes using a gyro to sense attitude. It avoided the error in the previous Uhlan gear design, which had been due to use of a pendulum for attitude sensing. During initial acceleration this gave a spurious attitude signal which caused a deep and many times disastrous dive. Patent 2920596. Jan. 12, 1960.
26. A torpedo motion simulator for engineering purposes based on the torpedo equations of motion, including the water mass and inertia associated with the torpedo. Such a simulator was built for development purposes at Ford Instrument Co., possibly the first torpedo simulator.
27. A "strapped-down" navigation system not using any gimbals (developed on a contract in 1958). In a personal communication, Newell said he considers this to be one of his potentially most important inventions. Patents 3049294, Aug. 14, 1962; 2087333, Apr. 30. 1 Y63.
28. A scheme for developing an electric current from a hot rod and a magnetic field. This is the other invention that Newell considers to be potentially most important. Patents 3075096, Jan. 22. 1963; 3084267, Apr. 2. 1963.
29. Newell and Willard B. Constantinides developed a deck-tilt corrector which corrected gun angles approximately for the level and cross level angles of the deck.
30. The mechanical analog technology was extended in 1945 for the development of a bomber navigation trainer, mainly by Willard B. Constantinidesof Ford Instrument Co. It solved the equations of motion of an airplane with far greater generality, realism, and precision than the contemporaneous pneumatic computers in the famous Link trainers, which dealt only with small linear perturbations about steady flight. To record the trajectory of the airplane as projected on the horizontal plane, the Ford simulator drove electrically and remotely a mechanical "crab" that drew a curve on a large sheet of paper on the floor.
31. A scheme for using resistors (standard but trimmed to precise values of a 1 000- 1 range) to obtain amplifier input gains, which was patented.

In the **foregoing list.** the items that were mainly electrical, as distinguished from mechanical or hydraulic. were nos. 12, 13. 14. 16.20.29. and 31.

Many more people than have been mentioned played notable roles under Ford and Newell. Certainly the following at least also deserve to be named here: Ray Jahn, George Crowther. George Hamilton. Charles Buckley, Walter Conable (the nephew of H.C. Ford), John Kallenberg, Howard Brevoort. and Elmer Garrett. During World War II they were assisted by Charles Henrich, Charles Pond, Kenneth Crawford (brother of Perry). Rasmus Figenschou (of Norway). John Hauser, George Licske. Mrs. George Elder (née Athena Rosarkv). Alois Mertz. and the author and other, then junior, design engineers.