Between Human and Machine

Feedback, Control, and Computing before Cybernetics

David A. Mindell

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Taming the Beasts of the Machine Age

The Sperry Company

Sperry's Reining In

In 1940 the Sperry Corporation's engineering graphics department hired Alfred Crimi, an Italian immigrant fresco and mural painter, to make perspective drawings. Crimi had greater talents, however, and before long he was working out of a private studio at the company, making sketches and murals of Sperry's products and production lines. Crimi painted a pressure chamber for high-altitude flight training, portraying the pilots as cubist-like robots enveloped in the cylindrical structure. He drew the company's aircraft turrets, making the gunner's body transparent, "as though seen through an X-ray," with mechanical elements taking on the role of vital organs. *Life* magazine published his sketches at the height of the war, as part of a profile of Sperry's products.[1] Crimi captured the strange blurring of the human-machine boundary effected by Sperry's control systems better than Sperry's corporate photographers were able to do. In Crimi's artwork the human operator is surrounded by the machine, is intimate with the machine, becomes the machine, reining it in (see, e.g., Fig. 3.1).

By 1940 the company could write coherently about "the inability of the unaided man to operate his weapons": "His airplanes have become so big and fly so far that he must have automatic pilots instead of flying by hand. The machine gun turrets must be moved by hydraulic controls. The targets of his antiaircraft guns now move so fast in three dimensions that he can no longer calculate his problems and aim his gun. It must all be done automatically else he would never make a hit."[2] This statement, like

Image not available.

Fig. 3.1. Sketch by Alfred Crimi of a Sperry ball turret for the B-17 bomber, 1941. Note the eyepiece for the lead-computing gunsight. Courtesy of Hagley Museum and Library.

Crimi's work, epitomizes three decades of control engineering at Sperry. During much of that time the idea of controls as extensions of the human was still evolving, and the company could not articulate its goals so clearly. Rather, Sperry engineers worked out their ideas and expressed themselves by building machinery with different types of feedback, different roles for human operators, and different types of systems. They developed skills in feedback, data transmission, mechanical computers, and power drives. Sperry's engineering culture of control systems resulted from military demands, engineering research, and manufacturing constraints.

Sperry's engineering culture developed around three types of products, with varying degrees of success: automatic pilots for ships and for aircraft and antiaircraft fire control systems. As with naval fire control, Sperry's experience not only concerns the evolution of control systems but connects that history to that of American industry and its relationship to the military. Government support allowed Sperry to experiment with risky technology in peacetime, setting it up for large-scale expansion when war came. Heavily emphasizing engineering, the company relied on technology for its competitive advantage, often leaving a field when it generated competition and sometimes being forced out. Sperry built long-term relationships with officers and military organizations in the United States and abroad and frequently hired military personnel for special projects (Sperry reportedly recruited graduates of the Naval Academy who had failed the eye exam). Military services paid Sperry Gyroscope to make intricate, precise mechanical devices in small numbers at relatively high costs, but the company also excelled at manufacturing these controls for commercial customers around the world. These skills paid off handsomely during World War II, as Sperry Gyroscope's sales for simple military devices skyrocketed. In the critical area of computing, however, manufacturing challenges exceeded the company's abilities, opening the door for other approaches.

Elmer Sperry referred to airplanes as "beast[s] of burden . . . obsessed with motion." This suggestive metaphor captures the vision of control systems he imparted to his company. The phrase projects animism and autonomy onto machinery—not an animism of intelligence like the "thinking machines" of later decades but an animism of the body, more akin to horses than to calculators. Machines needed control systems, in Sperry's words, because of their "constant unstable equilibrium."[3]

Compass and Pilot

As we have seen, Sperry Gyroscope first achieved commercial success with the gyrocompass for ships. By the end of World War I the gyrocompass had become an accepted and reliable device. Despite its frustrations in naval gunnery, the company profitably busied itself outfitting the world's fleets, both civilian and military, and Elmer Sperry won acclaim as a great American inventor and engineer.[4]

The gyrocompass included a phantom to transmit the position of the spinning gyro without interfering with its motion, but overall the machine remained a sensor and a reference. The data from a gyroscope proved steady and solid, however, so it was an

Image not available.

Fig. 3.2. The Sperry gyropilot, "Metal Mike," showing the clutch for disengaging the unit physically from the ship's wheel. Courtesy of Hagley Museum and Library.

ideal candidate for incorporation into a larger control system. Such a system made marketing sense as well, for customers who already owned the sensing device could buy additional equipment to complete the control loop.[5] In 1922, resuming a project it had started before the war, Sperry Gyroscope introduced the "Gyro-Pilot" (Fig. 3.2). This device connected the gyrocompass back through a ship's wheel, in a feedback loop that kept the ship automatically on course. It used an electric motor connected to the wheel via a chain to actually steer the ship in response to changes in the gyro reading. Elmer Sperry anthropomorphically called it the "iron quartermaster," and it quickly acquired the nickname "Metal Mike" both within industry and among the public. No human mediated the feedback loop; those who saw the device turning a ship's wheel often commented on its uncanny nature.

Sperry sales literature played on this novelty and mystery. One promotional pamphlet, *A True Story of the Devil,* tells a racist tale of a ship captain sailing in the Mediterranean. This white man invites an Arab captain, an experienced and able seaman, aboard the vessel to see it being steered automatically by the Sperry gyropilot. The

Arab sees the wheel operating by itself and stands in awe. After much searching for hidden ropes or some other source of the trick, he remains incredulous, convinced that the ship must be possessed by the devil. The American captain explains that the ship is being driven by an angel that only Christian believers can see. If the Arab were to convert from his "godless" ways, he too would see how the ship drives itself.[6] The ad makes the point that although ships may have been "beasts of burden," the gyropilot made them seem intelligent and domesticated (and Christian).

Because the gyropilot did not require a person to operate it, questions arose about its relationship to human operators. Some believed it could never replace the tacit knowledge embedded in an expert helmsman. Elmer Sperry countered by arguing that the helmsman's skill inhered in the ability to "anticipate" the ship's motions and that he had incorporated such a feature into the gyropilot.[7] Sperry Gyroscope offered as an add-on product a paper recorder to plot minute changes in course over time. The traces, the company claimed, would display in graphical form the limitations of a human operator:

> These records clearly show that even the best of men are not constitutionally adapted to perform this purely mechanical task [steering]. The man's powers of attention quickly become fatigued, he fails to detect small deviations from the course, these small deviations quickly become large deviations, too much or too little rudder is applied and the ship performs a sinuous course. The result is waste of power, both in the steering engine and the main engines.[8]

The course recorder also exposed differences between individual helmsman, as well as any variations in the quality of steering during a particular watch. In a tone that cannot have been comforting to working mariners, a common Sperry ad portrayed the gyropilot as a man looking for work:

> Wanted—a permanent position on board ship as a wheelsman. Have had experience in steering every type of merchant ship, can steer courses more accurately than others and use less rudder. Am sober, intelligent, strictly attentive to business, never ask for time off, do not talk back, am not affected by bill of fare or poor cooking, in fact do not eat at all. Wages wanted, only 54 cents per day for 24 hours service.
>
> [Signed]
> Sperry Gyro Pilot.[9]

“Helmsman regarded the course recorder as a kind of mechanical company spy,” *Fortune* magazine reported, “and the marine gyropilot as a wicked device meant to send them into technological unemployment.”[10] As Stuart Bennett noted in his study of instruments in the process industries, feedback devices were accompanied not only by claims of improved accuracy but also by social questions about obedience and reliability.[11]

These advertisements portrayed the human steersman as a weak link in the system. Yet customers in the traditional maritime businesses hesitated to relinquish such an important function to a machine. The company therefore hastened to assure prospective users that if they ceded control, they could grab it back anytime. The gyropilot included a large lever to physically disengage the unit, returning it to manual operation, assuring that “the regular ships *control is instantly available for emergency.*”[12] While it usurped control of the steering function, the gyropilot gave the human another task: control of the gyropilot itself.

Initially the human pilot had only one way to steer the ship: by turning the wheel. The gyropilot increased the number of inputs to seven. With the autopilot disengaged, the original wheel still worked as before. Metal Mike itself had a smaller wheel, used for setting the heading to hold (in another mode this wheel could also operate the rudder directly). The “weather adjustment,” in today’s parlance a *deadband,* allowed the ship to yaw a certain amount without initiating a correction. “Initial rudder adjustment” provided a means for “meeting” the helm as it returned to course, easing off on the rudder as it approached the proper course. Sperry called this “anticipation”; today it is termed *derivative gain.* “Rudder ratio adjustment,” or *gain* in today’s terms, determined the amount of rudder required to bring a particular ship back on course. Some of these tended to be permanent settings, varying only from ship to ship, while others needed frequent tweaking. In fact, the control system (like all closed-loop systems) required proper “tuning” to perform most efficiently, and sometimes even to operate at all.

This is not to imply that Metal Mike did not save labor; by keeping the person out of the feedback loop it kept the ship on course and relieved the operator of significant workload. Yet more than eliminating the steersman, the gyropilot altered the character of his job. He set the desired course and changed it in accordance with navigation. He also adjusted the instrument for changing weather conditions and different speeds (as often as once per hour).[13] And most important, he controlled when the automatic steering was put in effect; entering a harbor or avoiding an obstacle, for example, would not call for automatic control. The helmsman engaged and disengaged the autopilot according to the circumstances, literally trading or exchanging control between human and machine. Person and beast worked together, each making up for the other's limitations.

As with the earlier gyrocompass, the navy's interest in the gyropilot extended beyond that of commercial users. The navy cared less about labor problems and barely at all about labor costs, instead emphasizing accuracy and precision. Automatic piloting allowed better course tracking for maneuvers; more accurate courses meant more constant speeds and better firing solutions. It also had different implications for human operators. The company pointed out that in naval settings the ideal of a robotlike helmsman broke down under conditions of extreme stress: "It has been assumed that many of the helmsman's reactions under the stress of battle conditions will be mere automatic reflexes, inculcated by previous training until the familiar tasks may be performed without conscious thought. While it is a fact that predictions of human reactions must be based on averages, the man at the wheel is unfortunately not an average but an individual." Here Sperry's literature displays a certain sophistication, balancing the need to design machines for average users with the need to accommodate variation. The unique individual, with all his judgment and skill—and possibly panic, uncertainty, and mistakes—reemerges from the average in battle, potentially invalidating the machines. The solution to this quandary was not less machinery but more, to shift the operator's burdens to less stressful time periods. According to the company, once set up and adjusted, the gyropilot would literally sail through battle: "The consistent, machine-like precision of the Gyro-Pilot cannot fail to enhance the qualities which are all-essential in battle. True, man can never be displaced by the machine, but his function may well become that of the stand-by observer, rather than prime-mover in the action where perfection in every detail must ever remain the objective."[14] Combat, that most chaotic and unpredictable human situation, called for the highest precision and certainty that technology could provide. The human steersman need only stand by and watch.

Sperry's automatic pilot for ships was a classical feedback loop. It connected a sensor (the gyrocompass), through an amplifier (an electric motor that drove the ship's wheel), to an actuator (the ship's steering gear). It represented the world in a single dimension, heading, and used that representation to directly control the ship; the human intervened only to set the loop in motion and to adjust its parameters. Hence, the gyropilot raised social questions about the operator's nature and role. Was the helmsman a skilled technician? An unreliable element in a labor system? A steady warrior or an unstable observer? On ships these questions surrounded a traditional task that had been accomplished for centuries without mechanical intervention—that of the steersman, namesake and icon of Wiener's cybernetics. Soon Sperry automated a new kind of operator, the airplane pilot, addressing tasks that increasingly could not be accomplished by humans alone.

Automatic Pilots for Aircraft

In aviation, as in the marine market, Sperry first achieved commercial success with instruments. To make the transition from a technical curiosity to a mainstream technology, the budding aviation industry in the 1920s needed to demonstrate reliable operation. Commerce needed to bring the wild airplane into the world of acceptable risk and repeatable scheduling, and the military wished to bring the chaotic aerial domain into its quantified purview. During World War I Sperry conducted a difficult development program in gyroscopic aircraft instruments for the navy. (Elmer Sperry's navy liaison for this program, the MIT graduate Luis de Florez, would later be the primary sponsor for the Whirlwind digital computer.) Sperry introduced a gyroscopic turn indicator in 1918, then a "Directional Gyro" and a gyroscopic "Artificial Horizon" in 1930. Sperry's first high-volume products, these instruments became standard on airplanes produced in the United States through World War II. Sperry's instruments, many of them based on gyroscopes, gave pilots feedback on the state of the airplane that they could not get from other sources, helping expand the operating envelope of aviation into adverse weather conditions. The directional gyro and the artificial horizon became part of the standard suite of airplane instruments and remain so today.

Sperry's aircraft instruments also proved stable enough to drive feedback loops. Just as it had introduced Metal Mike to close the loop around marine gyrocompasses, Sperry closed the loop around its aviation instruments with an autopilot. The product culminated a long series of experiments. As early as 1914 Elmer Sperry and his son Lawrence demonstrated the ability to stabilize aircraft with large gyroscopes. During World War I they built an autonomous flying bomb, or "aerial torpedo," under government contracts.[15] This device failed because the engineers could not achieve reliably stable flight without a human operator to monitor the control loops, but Sperry Gyroscope fared better with a control system that worked in conjunction with a human pilot

Lawrence Sperry died in an airplane crash in 1924, so it remained for Elmer Sperry

Jr. to develop a fully automatic autopilot in cooperation with the army in 1925–29. The army wanted the autopilot because it could keep an airplane stable during a bombing run, and automatic pilots became critical elements of precision bombsights. The company introduced its first autopilot in 1931, designated A-1. Like earlier attempts, the mechanical device employed electrically driven gyroscopes as sensors and electric motors as actuators. It could stabilize an airplane in pitch and yaw, but it also coordinated the aileron and rudder to stabilize heading, which earlier devices could not do. The innovative A-1 had reliability and maintenance problems and required frequent adjustments, but several were delivered for military and commercial use.

Sperry's refined model, the A-2, used air-driven gyros and pneumatic-hydraulic actuators for better reliability. It could also hold altitude, by amplifying the signal from a delicate pressure sensor through pneumatic actuators. Like the gyropilot for ships, the A-2 autopilot had a disengagement clutch for emergencies and several knobs that enabled the pilot to "control movement in all three planes without disengaging the autopilot." The pilot now controlled the autopilot, which controlled the plane. The company and the army followed up with an intensive program for pairing bombsights with autopilots. This pairing allowed a bombardier to look through the sight and actually control the aircraft while lining up the sight, an intimate coupling that brought the operator inside a more complex control loop.[16] The A-2 made the automatic pilot a practicable device and a commercial product. It did not eliminate the human operator, but it relieved the pilot of work and reduced fatigue. Nobody illustrated the changes for pilots wrought by the new controls better than Wiley Post.

Wiley Post, Early Cybernetic Hero

Ironically, the man who popularized the automatic pilot was himself uniquely skilled, for Wiley Post made his mark as a pilot particularly close to his craft. In 1926, while working as a laborer in the Oklahoma oil fields, Post lost his left eye in an industrial accident. He literally replaced it with a machine, using his workmen's compensation to buy his first airplane. As one early colleague recalled, "He didn't just fly an airplane, he put it on." Another remembered Post as "as near to being a mechanical flying machine as any human who held a stick."[17] When flying, Post wrote, "I tried my best to keep my mind a total blank. I do not mean that I paid no attention to the business of handling the ship. I mean that I did it automatically, without mental effort, letting my actions be wholly controlled by my subconscious mind."[18] For Wiley Post, the autopilot merely replicated feedback loops inside himself.

Image not available.

Fig. 3.3. Wiley Post and the *Winnie Mae,* in which he made his around-the-world solo flight with a Sperry autopilot. Reprinted from the sales pamphlet *Round the World with the Sperry Pilot,* SGC Papers.

After leaving the oil fields, Post found a job ferrying Lockheed Vega airplanes from the factory to customers. Here he gained experience with the problems of "blind flying" through clouds and bad weather, relying on early Sperry gyroscopic instruments to keep his bearings. In 1931 Post and his partner, Harold Gatty, who had trained Charles Lindbergh in navigation, made headlines by piloting a Vega named *Winnie Mae* around the world in record time (Fig. 3.3).[19] For the round-the-world flight Post grouped his instruments right in front of his one eye and modified the cockpit so that he could fly with one foot on the rudder pedals and one hand on the wheel. As Preston Bassett, president of the Sperry Corporation, later remarked, "All combined, the setup was that of a man flying around the world with one eye, one arm, one leg, and two instruments. You will see that we are building toward a very good servomechanism."[20]

In 1933 Post repeated the trip by himself. Like Lindbergh six years earlier, Post struggled with fatigue, and he fell asleep on several occasions. Yet the sleeping Post did not spiral fatally to earth as Lindbergh had feared. The *Winnie Mae,* though absent its operator's steady hand, kept flying straight and level. Post had one of the first Sperry A-2 automatic pilots (he bought the device, but after his flight the company would not accept payment) (Fig. 3.5). The machine was not perfect; sometimes it failed and Post

Image not available.

Fig. 3.4. Aviatrix Amelia Earhart *(left)* inspects a Sperry automatic pilot of the type she would use on her fateful around-the-world flight. At right is Sperry president Thomas B. Lea. Courtesy of Hagley Museum and Library.

had to fly manually. The two worked together, trading control, playing on each other's strengths and making up for each other's weaknesses. Post's machine freed him for other functions, such as navigation, but primarily it allowed him to nap, considerably reducing his fatigue, the greatest obstacle on his record flight.[21]

Like Lindbergh's trip six years earlier, Post's flight was an accomplishment of both the human operator and the engineers and craftsman who had made his machinery. The blue-collar Post never achieved the acclaim of Lindbergh, but public exposure of the round-the-world flight brought the Sperry A-2 and automatic control of aircraft into public view. Amelia Earhart installed a Sperry autopilot in her flying laboratory and used one on her ill-fated around-the-world flight (Fig. 3.4). "The days when human skill and an almost bird-like sense of direction enabled a flier to hold his course for long hours through a starless night or over a fog are over," commented the *New York Times,* predicting the end of the era of heroic pilots. "Commercial flying in the future will be automatic."[22] Trans World Airlines (TWA) equipped its fleet of new DC-3 aircraft with the device, and by 1940 Sperry had sold 2,600 of them. As with the marine gyropilot, the coupling between perception and articulation was direct and intimate. The human operator tuned and supervised the feedback loop, trading control.

Image not available.

Fig. 3.5. Sperry gyropilot for aircraft installed in Wiley Post's plane: rectangular console in the dashboard, pneumatic actuators below. Courtesy of Hagley Museum and Library.

The Sperry Corporation in the 1930s

Post's flight demonstrated the great potential of aviation controls in an exciting and rapidly changing industry that swept up Sperry Gyroscope. In 1929, the year before his death, Elmer Sperry sold his stake in the company for $4 million. In a heady, chaotic time for the airplane industry Sperry Gyroscope became part of North American Aviation, a conglomerate that included several airlines and aircraft manufactures.

Tom Morgan, the man who worked with Hannibal Ford on the first trials of the gyrocompass in 1912, became president of Sperry Gyroscope, and soon thereafter he became president of North American. General Motors acquired North American in 1933, and the fallout from that transaction created the Sperry Corporation. With Morgan as president, Sperry now became a holding company for smaller firms brought in through acquisitions (including Sperry Gyroscope Ltd., the English subsidiary).[23]

Reginald Gillmor, who had overseen the installation of the earliest gyrocompass, aboard the *Delaware,* and who had transferred British fire control technology to the United States, now headed the Sperry Gyroscope subsidiary of the Sperry Corporation. The company's business was distributed among the following markets: 30 percent naval, 30 percent military, 30 percent marine, and 10 percent aeronautical. The aeronautical sector grew most quickly. Morgan committed the company to the field and dedicated a substantial portion of its research and development budget to aircraft. By 1937 aviation accounted for half of Sperry Gyroscope's business.[24] Through the depression, Sperry Corporation's research and development budget rose steadily, averaging 2.5 percent of income from sales from 1933 to 1940, mostly supporting its large laboratory in Garden City, Long Island.[25]

Yet for the Sperry Corporation overall, control encompassed more than aircraft. During the early 1930s the Sperry Corporation took shape as an integrated control-system company. It purchased Ford Instrument in 1933, which remained under the leadership of Hannibal Ford, who thus found himself once again a Sperry employee. Ford Instrument still exclusively made naval fire control computers for BuOrd, operating out of three separate plants in Long Island City. Though owned by the same holding company, Sperry Gyroscope and Ford Instrument shared remarkably little technology well into the 1940s.

Sperry Gyroscope and Ford Instrument emphasized the perception and integration aspects of control systems, but several acquisitions during this period brought the corporation expertise and products for articulation as well, and tied the company to other domains of American industry. In 1935 Sperry acquired the Waterbury Tool Company of Connecticut, a maker of large, variable-speed hydraulic transmissions. Waterbury's hydraulic gear moved turrets for large naval guns and shell hoists, cranes, and numerous other shipboard machines; one ad called them the "'nerves' and 'muscles' for superhuman tasks."[26] In 1937 the Detroit-based Vickers Inc., the country's largest maker of oil hydraulic machinery, came into the fold. Vickers (not related to the British arms firm, Vickers Ltd.) specialized in small, high-powered controls for industrial applications, including paper making and cable manufacturing. Harry Vickers founded the company in 1920 with financial backing from Fred Fisher, of the automotive industry's Fisher Brothers. Fisher now became the single largest stockholder in the Sperry Corporation, with about 2.5 percent of its shares. (He remained on the board until his death in 1941, when he was replaced by his brother, Charles.) In 1940 Waterbury combined with Vickers to create a product line that covered the full range of hydraulic power devices.[27] Other than this consolidation, Morgan chose not to integrate his companies as divisions under the Sperry Corporation but rather to keep them as subsidiaries so that they would retain their separate cultures.

With these subsidiaries devoted to instruments, computers, and actuators, the Sperry corporate structure itself now mirrored a feedback system.[28] Indeed, the company often sold systems that included components from its multiple subsidiaries. Within the Sperry Corporation, however, fire control for the navy remained the exclusive domain of Ford Instrument. But this field was itself starting from scratch on the new problem of antiaircraft defense, and to attack this new challenge Sperry Gyroscope teamed up with the army.

Antiaircraft Fire Control

While Sperry Gyroscope was improving airplanes with flight controls, it also built a business destroying them. In fact, the company's interwar work in control systems culminated in antiaircraft fire control. Because the problem of antiaircraft fire control required data of diverse origins and varying quality, unlike in marine or aviation controls, human operators became intimate parts of control loops as interpreters of the data. Antiaircraft fire control thus enables a useful comparison with marine and aviation automatic pilots because it shows how problems of machine representation affected both the role of human operators and the techniques of manufacturing. Also, Sperry's antiaircraft projects laid the groundwork for research into problems of prediction, computing, and human-machine interaction during World War II. When Norbert Wiener began thinking about human-machine interaction, he was addressing the problem as defined in the 1920s by Sperry and the army.

Like hitting a distant battleship, shooting an airplane out of the sky is essentially a problem of leading the target. Aircraft developed rapidly in the 1920s, and their increased speed and altitude rapidly pushed the task of computing this lead out of the range of human reaction and calculation. Fire control equipment for antiaircraft guns helped human gunners to accomplish a task that was beyond their natural capabilities.

Measuring instruments had long been part of an artilleryman's tool kit. During World War I the Army Ordnance Department procured a broad array of fire control instruments for land artillery, including optical rangefinders, gunsights, periscopes, plotting boards, and traditional gunner's quadrants. American industry geared up for large-scale production, but the war ended before American-made fire control devices reached the front in large numbers. Nevertheless, the efforts did build up domestic capacity in precision optics, bringing a number of companies into the fold that would continue to build fire control instruments for decades: Eastman Kodak, Bausch and Lomb, Keuffel and Esser, Kollmorgan Optical, Leeds and Northrup, and National Cash Register (NCR).[29]

Amidst this buildup, fire control for antiaircraft guns underwent some preliminary development. Artillery officers used slide rules to calculate lead angles based on optical sighting of targets. These slide rules were incorporated into mechanized boxes; an operator would dial in data with knobs, read out an answer on a dial, and telephone azimuth and elevation to those operating the guns (*azimuth* was the term used by the army for the gun's rotation, while the navy used *train;* both services used *elevation*). Elmer Sperry, as a member of the Aviation Committee of the Naval Consulting Board, was familiar with this technology, and he did some work developing bombsights, guided bombs, and aircraft gunsights. The Army Ordnance Department knew of Sperry's work in naval fire control and invited him to submit a proposal for directing antiaircraft fire. Sperry came up with two instruments, but his company was unable to produce these devices in quantity during the war.[30]

When the war ended in 1918, the army undertook no new work in antiaircraft fire control for several years. In the mid-1920s, however, it began to develop components for antiaircraft systems, including stereoscopic height-finders, searchlights, and sound location equipment (Fig. 3.6). The latter two involved Sperry Gyroscope. Sperry had made its first searchlights in 1916 and sent them to war in 1917.[31] After the war, searchlights came to account for a significant portion of Sperry sales, for both military (navy and army) and commercial applications, and would continue to do well into World War II.

Within the army, antiaircraft came under the purview of the Instrument Department of Army Ordnance, located at the Frankford Arsenal in Philadelphia. There, in 1925, Major Thomas Wilson began developing a calculating machine for antiaircraft fire control based on the system of director firing in naval gunnery. Wilson's device accepted data as input from perception components, performed calculations to predict the future location of the target, and articulated direction information to the guns.

With Wilson's director, the components of an antiaircraft battery remained independent, linked only by voice telephone. "No sooner, however, did the [antiaircraft] components get to the point of functioning satisfactorily within themselves," recalled Sperry's then chief engineer, Preston Bassett, "than the problem of properly transmitting the information from one to the other came to be of prime importance."[32] Tactics and terrain considerations often required that different fire control elements be separated by up to several hundred feet. As in the early naval systems, observers telephoned their data to an officer who manually entered the data into the calculating machine, read off the results, and telephoned them to the gun installations. From its experience in making gyrocompass repeaters aboard ship, Sperry Gyroscope knew how to automate these communications, so the army approached the company for help.

Image not available.

Fig. 3.6. Sperry sound-ranging equipment and human operator. Courtesy of Hagley Museum and Library.

To Elmer Sperry it looked like an easy problem: the calculations resembled those in a naval application, but the physical platform, unlike a ship at sea, stood on solid ground. The army system also had its own electrical supply and stood physically separate from the guns, precluding the synchronization problems that plagued Sperry's system aboard ships. In 1925 Sperry engineers visited Major Wilson at the Frankford Arsenal and expressed interest in working on the problem. Sperry stressed his company's experience with the navy, as well as its recent developments in bombsights, which he described as "work from the other end of the proposition."[33] Indeed, bombsights had to incorporate numerous parameters of wind, groundspeed, airspeed, and ballistics, so antiaircraft directors really were reciprocal bombsights. (One reason that antiaircraft fire control equipment worked at all was that it assumed attacking bombers had to fly straight and level to line up their bombsights.) Elmer Sperry's advances to Wilson were warmly received, and in 1925 and 1926 Sperry Gyroscope built two data transmission systems (one traditional step-by-step, the other synchronous) for the army's gun directors. Major Wilson died in 1927, and Sperry Gyroscope took over the entire director development from the Frankford Arsenal with a contract to build and deliver a new director to the army.

Beginning with this project, Sperry undertook a small but intensive development program in antiaircraft fire control that would last more than fifteen years. The company set up a separate department with its own facilities and personnel and gradually developed a cadre of experts. Heading the effort was Earl W. Chafee, an engineer whose strong personality and free managerial hand allowed him to dominate Sperry's fire control work into the 1940s. The company financed its engineering internally, selling directors in small quantities to the army, mostly for evaluation, for only the cost of production. The army called these "educational orders," intended "to provide means for at least a few industrial facilities to familiarize themselves with the technique and special skill required to produce the material."[34] Sperry never sold more than twelve of any of the nearly ten models it developed before 1935; the average order was five. Sperry Gyroscope offset some development costs by sales to foreign governments, especially Russia, with the army's approval—the very type of arrangement that had so annoyed the navy.[35]

For most of the twenties and thirties, Sperry's antiaircraft work concentrated on aiming large guns (3–4 inches in diameter) firing exploding shells to relatively high altitudes to reach attacking bombers. The shells were not intended to hit the target directly but rather to explode nearby at some predetermined time after firing. Since this scenario represented the most difficult antiaircraft situation at the time, its techniques diffused into other applications, including coastal defense and traditional artillery.[36] The antiaircraft problem proved difficult enough, but aeronautic technology itself was rapidly changing. In 1925 bombers flew at 100 mph at relatively low altitude. This speed more than tripled in the next ten years, and the bombing altitude rose to well above 15,000 feet. In more ways than one Sperry was shooting at moving targets.

Increasing aircraft speeds and altitudes created a number of problems. Tracking and prediction were the same as in naval gunnery, but with a third dimension and with different distances and times. Once fired, shells travel with ever-decreasing velocity due to gravity and air resistance. Typical shells of the 1930s would take 15 seconds to reach 5,000 feet, and double that to reach 8,000 feet. A plane traveling at 100 mph at 5,000 feet would travel about 750 yards horizontally (toward the target) dur-

Image not available.

Fig. 3.7. Antiaircraft trajectories and lead times for different bomber speeds. Reprinted from Sperry Gyroscope Company, *Anti-Aircraft Gun Control*.

ing the shells' time of flight. Thus the lead for the gunner would be 750 yards. A plane traveling at 250 mph at 8,000 feet would travel 3,660 yards (more than two miles) during shell flight, requiring a lead nearly five times greater than that for the slower, lower plane. In either case, the shell would need to be fired, not at the plane itself, but at its expected location after the time of flight. The longer the time of flight, the more difficult this prediction. Furthermore, the problem had an inherent feedback loop because prediction could only be accomplished when the time of flight was known, but time of flight depended on the aiming point, itself the output of prediction.

Tactics further complicated prediction. For antiaircraft fire to have real defensive effects, it needed to shoot down (or at least scare off) attacking planes before they released their bombs. This limitation reduced the time available for the director to produce a firing solution: tracking could begin only when the attacking aircraft came into visual instrument range, and the shell had to be fired at least one "time of flight" before the bomb release point (Fig. 3.7). For a bomber flying 100 mph, if the antiaircraft guns were placed right at the bomber's target, the aircraft would be within visual range for 6 minutes and within the effective range of the guns for 2.5 minutes. For a bomber flying 250 mph typical of the late 1930s, gunners could only see the target for about 2 minutes, and they could effectively fire at it for 1 minute.[37]

One way to improve the situation would be to move the antiaircraft director and battery forward of the target, allowing it to engage attacking planes well before their bomb release points. A successful prediction depended, however, on an assumption of straight and level flight, which only held during a bombing run, when the plane needed to fly steady to align its own bombsight. An antiaircraft battery too far ahead of the target would catch the bomber before its bombing run, when the straight and level assumption was not yet valid.[38] Nevertheless, if the antiaircraft system could completely solve the problem for a given zone, it could force attackers to maneuver or climb to a higher altitude, making their job more difficult and achieving a partial tactical advantage.

Inside a Sperry Gun Director

After producing several prototypes, in 1930 Sperry developed a gun director, designated T-6, which the army accepted and "standardized" (i.e., put into operation).[39] The T-6 was the first American antiaircraft director to be put into production, as well as the first one the army formally procured, so it is instructive to examine its operation in detail. Such an analysis also clarifies the basic features of the antiaircraft problem that would drive the development of control systems through World War II (and, in modified forms, through the Cold War and even into the era of ballistic missile defense). A technical memorandum written by Sperry's Earl Chafee in 1930 lays out the function and purpose of the machine.[40]

"The heart of the gun control system is the Computer," writes Chafee, articulating his sense of the director as the center of a distributed control system. Historians have frequently noted that before 1945 the term *computer* referred to human operators, usually women, who ran calculating machinery. Not so in fire control, where Chafee and others used the term at least fifteen years earlier to refer to these mechanical, analog gun directors (though they were not stored-program computers in the modern sense).[41] In his report, Chafee describes in detail the workings of a mechanical analog computer that connected up to four 3-inch antiaircraft guns and an a rangefinder into an integrated system (Fig. 3.8).

As in Sperry's naval fire control system, the antiaircraft director used data trans-

Image not available.

Fig. 3.8. Layout of the Sperry T-6 antiaircraft director. The human is shown only to indicate the scale.

mitters similar to those that connected gyrocompass repeaters aboard a ship to provide its three primary inputs. First, the target range came from a stereoscopic rangefinder (with one operator) similar to those used in naval fire control. The second and third variables came from two human operators using telescopes mounted on the director itself to track the target's azimuth and elevation. Each sighting device had a data transmitter that sent its angle reading to the computer. The computer received these data and incorporated manual adjustments for wind, muzzle velocity, air density, and other factors. It calculated three output variables for the guns: azimuth, elevation, and the shell's time of flight. The last, manually set into a fuze before loading, determined the amount of time after firing it would take to explode.

The computer performed two major calculations. First, *prediction,* or leading the target, modeled its motion and extrapolated it to some time in the future. Second, the *ballistic* calculation figured how to aim the gun to make the shell arrive at the desired point in space and explode; it corresponded to the traditional artilleryman's task of looking up data in a precalculated firing table. To perform the prediction, the Sperry director, like the Ford Rangekeeper, converted its input information from polar to Cartesian coordinates. The mechanisms projected the movement of the target into a horizontal plane and derived the velocity from changes in position. The director then multiplied that velocity by the prediction time to determine a future target position and then converted the solution back into polar coordinates for output. Sperry called this approach the *plan prediction method* because it represented data on a flat plan as viewed from above. (The familiar radar target display, introduced years later, in which a beam rotates sweeps around a round tube to reveal targets, became known as the *plan position indicator,* or *PPI,* an appellation inherited from this method of computation.)

Chafee did not use the term *analog*, but his machine represented the world with a physical model. "The actual movement of the target is mechanically reproduced on a small scale within the Computer," he wrote, "and the desired angles or speeds can be measured directly from the movements of these elements."[42] Once the machine had a good model, the computation became relatively straightforward. Generating the model and ensuring that it faithfully represented the world posed the major technical challenge and required human intervention.

The Sperry director also used a mechanical representation for ballistics, employing a *mechanical firing table.* Traditional firing tables were numerical lists of gunnery solutions that indicated how to set the gun for specified values of range, wind, temperature, and other factors. Sperry replaced the firing table with a "Sperry ballistic cam." This three-dimensional, cone-shaped device effectively stored the table mechanically and used a pin to look up answers (Fig. 3.9). Two independent variables were input by the angular rotation of the cam and the longitudinal position of the pin, which rested on top of the cam. As the pin moved up and down the length of the cam, and as the cam rotated, the height of the pin reflected the solution to part of the ballistics problem. The T-6 director incorporated eight ballistic cams, each solving for a different component of the computation. To adapt a director to a different type of gun, one simply replaced the ballistic cams with a new set, machined according to different firing tables.[43] Foreign governments, for example, would supply Sperry with firing tables for their own guns, and the company then machined custom cams and produced special directors. The ballistic cams constituted the permanent memory of the computer, roughly comparable to what today we would call *ROM,* or read-only memory.

Together, ballistic and prediction calculations formed a feedback loop (Fig. 3.10). Operators entered an estimated time of flight for the shell when they first began tracking. The predictor used this estimate to perform its initial calculation, which fed into the ballistic stage. The output of the ballistics calculation then fed back an updated estimate of the time of flight, which the predictor then used to refine the initial estimate.

Image not available.

Fig. 3.9. Operation of the Sperry ballistic cam. Two variables are input by rotating the handles at the left. The pin rides along cam as it rotates, the height of the pin, *S*, providing the output value to be fed into another mechanism. In this example, for a given range and angular height of a target, the output, *S*, is the firing angle of the gun. Shaft inputs would replace handles in a real machine.

Thus "a cumulative cycle of correction and recorrection . . . brings the predicted future position of the target up to the point indicated by the actual future time of flight."[44]

A square box measuring about 4 feet on a side, the T-6 director mounted on a pedestal that allowed it to rotate (Fig. 3.11). Three crew members sat on seats, and one or two stood on a step mounted on the machine, revolving with the unit as the azimuth tracker followed the target. This arrangement provided comfortable, stable positions for the tracking operators. As the unit and the trackers rotated, however, the remainder of the crew, who stood on a fixed platform, had to shuffle around with it. While the rotation angles were small for any given engagement, it must have been awkward. Moreover, the T-6 computer required only three inputs—elevation, azimuth, and altitude—and produced only three outputs—elevation, azimuth, and fuze time—

Image not available.

Fig. 3.10. A simplified diagram of the system layout and data flow for the Sperry T-6 antiaircraft gun director computer.

yet it required *nine* operators. These nine did not include the operator of the rangefinder, which was considered a separate instrument, or the men tending the guns, but only those operating the director itself. What did these nine men do?

Manual Servomechanisms and the Sperry Director

The army's specification for the T-6 director required "minimum dependence on the 'human element.'" Sperry Gyroscope explained that "all operations must be made as mechanical and fool proof as possible; training requirements must visualize the con-

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Fig. 3.11. The Sperry T-6 director: *A,* spotting scope; *B,* north-south-rate dial and handwheel; *C,* future-horizontal-range dial; *D,* super-elevation dial and handwheel; *E,* azimuth tracking telescope; *F,* future-horizontal-range handwheel; *G,* traversing handwheel (azimuth tracking); *H,* fire control officer's platform; *J,* azimuth-tracking operator's seat; *K,* time-of-flight dial and handwheel; *L,* present-altitude dial and handwheel; *M,* present-horizontal-range dial and handwheel; *N,* elevation tracking handwheel and operator's seat; *O,* orienting clamp. Courtesy of Hagley Museum and Library.

ditions existent under rapid mobilization."[45] The memory of World War I rings in this statement. Even at the height of isolationism, with the country sliding into depression, design engineers considered the difficulty of raising large numbers of trained personnel in a national emergency. Designers also considered the ability of operators to perform their duties under the stress of battle. Thus, nearly all the work for the crew was in the follow-the-pointer mode inherited from naval systems: each man concentrated on an instrument with two indicating dials, one showing the actual value for a particular parameter and one showing the desired value. With a hand crank they adjusted the parameters to match the two dials and bring the error to zero. Sperry called the operators "manual servomechanisms."[46]

Figure 3.12 shows the crew arrayed around the T-6 director in an arrangement that today seems almost comical. Strange as this configuration seems, it reveals Sperry engineers' conception of the human role in the system. In this early machine one man corresponded to one variable, and the machine's requirement for operators corresponded directly to the data flow of its computation. The men literally supplied the feedback that made the system work, although Sperry's idea of feedback was rather different from today's: "In many cases where results are obtained by individual elements in the cycle of computation it is necessary to *feed these results back* into the mechanism or to transmit them."[47] Turning a shaft to eliminate the error between two dials is a classic servo problem, and Chafee acknowledged that "servo-motors" could do the job. Still, he claimed that "it has been found in many cases to be much easier to rely on a group of operators who fulfill no other function than to act as servomotors. . . . This operation can be mechanically performed by the operator under rigorous active service conditions."[48] The term *manual servomechanism* itself is an oxy-

Image not available.

Fig. 3.12. The Sperry T-6 director, mounted on a trailer, with operators. Courtesy of Hagley Museum and Library.

moron, for it acknowledges the existence of an automatic technology that might replace the manual method.

Indeed, servos already replaced two operators from the previous model. While the Sperry literature proudly trumpets human follow-the-pointer operations, it barely acknowledges the automatic servos, and even then it provides the option of manual follow-ups "if the electrical gear is not used."[49] Indeed, there was more to the human servo-motors than Sperry wanted to acknowledge; men still had to exercise some judgment, even if unconsciously. The data were noisy, and even an unskilled human eye could eliminate complications due to erroneous or corrupted data. The mechanisms themselves were rather delicate, and bad input data, especially if they indicated conditions that were not physically possible, could lock up or damage the machine.[50] The crew that operated the T-6 director corresponded exactly to the algorithm inside it, and at each stage they renewed the data and verified that they faithfully represented the world.

Because of these human interventions, Sperry could develop its machines to the point that the greatest uncertainties in the system stemmed not from integration but from perception and articulation. Readings from the stereo rangefinders depended greatly on the skills of the human operator, which were highly variable, even from day to day for a single person. Setting the fuzes introduced even greater errors, because the gun crews set them by hand as they loaded the shells, which introduced variations in time. But Sperry engineers conducted time and motion studies of the crews to standardize this operation and experimented with automating the actual gun pointing. Automatic control of the guns proved a difficult problem because significant power amplification was required to make the small signals produced by the computer drive the massive guns. Sperry's acquisition of Vickers and Waterbury provided the corporation with the skills it needed to design and manufacture hydraulic drives. By the end of the thirties the company had an electro-hydraulic remote-control system to move antiaircraft guns under remote control, which it produced by the thousands.[51]

Producing Computers in the 1930s

Throughout the 1930s Sperry continued to work with the army to develop antiaircraft computers. In later models servomechanisms replaced human operators in the computation cycle, reducing the number of human operators to four. Chafee designed the machines to be lighter, less expensive, and "procurable in quantities in case of emergency."[52] By the start of World War II the primary antiaircraft director available to the army was the Sperry M-7. It incorporated an altitude predictor for gliding targets, could accept electrical inputs from radio rangefinders, and implemented full power control of the guns.[53] This computer, culminating 15 years of work at Sperry, was a highly developed machine, optimized for reliability and ease of operation and maintenance. Its design capitalized on the strengths of Sperry Gyroscope: data transmission, intimate involvement with technical officers in the armed services, human mediation of the computation cycle, and manufacturing of precision mechanisms. It was an elegant, if intricate, device, weighing 850 pounds and including roughly 10,000 parts.

Still, producing the M-7 was not easy, and the difficulty limited its usefulness. The much-touted ballistic cams best illustrate the manufacturing difficulties of Sperry directors. These strangely shaped parts originated in the numerical firing tables provided by the army's Aberdeen Proving Ground. From the data in these tables a machinist would fabricate the cams directly, without going through the intermediate stage of blueprints. First, a rough cam would be cast, and then the machinist would drill hundreds of small holes, working from numbers on the artillery firing table. He would then file the cam and polish it, both smoothing the cam mechanically and smoothing the data mathematically. These operations required a great deal of time and skill, and ballistic cam manufacture proved a major bottleneck in Sperry's production of directors.

The process, with its flow of information from ballistics to machine control, gradually approached what would later be called *numerically controlled* machining. The historian David Noble has argued that numerically controlled machine tools emerged later as an effort to eliminate reliance on skilled machinists.[54] But the problems of cam cutting point to a different motivation: these parts were defined numerically from the beginning. Drawings for them never existed; their shapes came from firing tables and traveled through a human operator on their way to a mechanical part. The highly skilled machinists themselves worked from numbers, converting numerical data into a smooth physical representation (Figs. 3.13 and 3.14).

By 1941 manufacturing the ballistic cams, along with the other precision parts required for the gun directors, was seriously inhibiting Sperry's ability to meet its orders. Under pressure from the Army Ordnance Department the company subcontracted production of the M-7 to the Ford Motor Company (though cam production remained in-house). What followed was a remarkable episode wherein the precision manufacturing practiced at Sperry Gyroscope came into contact with classic mass production pioneered by Ford. The results revealed the limitations of both mass production and mechanical computers and spurred the later development of electronic computers for military control systems.

In 1943 Ford began to produce the directors in its Highland Park plant, the very space where the company first installed assembly lines to produce Model Ts. But Ford's techniques simply did not work when applied to mechanical computers.[55] Ford did not even begin large-scale production of the M-7 directors until three months after the original contract was to have been completed. The program eventually produced less than half of the original order of 1,856 directors and rarely exceeded half of the planned production rate of 200 per month.[56]

Sperry and the army explored two solutions to these production problems: simplifying the mechanisms of the computers and moving to electrical computations. Toward the first, the army adopted an English machine known as the "Kerrison director," named after its designer, renaming it the M-5 director for light antiaircraft guns. It had simplified (though less accurate) computations, resulting in simpler mecha-

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Fig. 3.13. Numerical control: manufacturing ballistic cams. First, holes were drilled into a cylinder, each hole corresponding to a data point from a ballistics table. In the background is such a numerical table. Courtesy of Hagley Museum and Library.

nisms that required only one ballistic cam. Sperry redesigned the M-5 for high-volume production in 1940 but passed responsibility for manufacturing it on to Singer Sewing Machine, Delco, and the Ford Motor Company.[57]

The other solution to the production problems—electrical computations—Sperry investigated but never pursued. In 1936 Sperry let a contract to Professor Nicholas Minorsky, of the University of Pennsylvania, to study the possibility of replacing the calculation mechanisms of its mechanical directors with electrical components. Minorsky had worked for Charles Steinmetz at G.E. and had done pioneering work in the 1920s on the theory of control systems for ship steering. He proposed a design for an electrical director, and Sperry asked one of its engineers, Bruno Wittkuhns, to evaluate it. He found Minorsky's plan "entirely too complicated and impracticable" but came up with a scheme of his own to convert a Sperry director to electrical compu-

Image not available.

Fig. 3.14. After the holes are drilled into the cylinder, the cams are then filed smooth by a machinist, who also serves to interpolate between data points, a digital-to-analog conversion. Three cams are crafted out of a single cylinder, and the data points are still visible as holes. Courtesy of Hagley Museum and Library.

tation, noting that electrical equipment was "well suited to mass production."[58] Wittkuhns employed follow-up motors with feedback to do the calculations, although his scheme still involved mechanical cams.

The company took no further action on an electrical director, but the episode makes an important point: electrical computers first appeared on Sperry's agenda because they were easier to manufacture. As we shall see, in 1940 an engineer at Bell Labs would "invent" the device Wittkuhns described based on an electrical replacement for the ballistic cams. How machines represented the world affected not only the design of the mechanisms and the role of their human operators but also the types of skills and resources required to produce them.

As industrial products and military instruments, Sperry Gyroscope's antiaircraft gun directors were only partially successful. When the NDRC was formed in 1940, among its first projects was the creation of standardized testing regimes for antiaircraft directors. These tests proved the Sperry machines to be seriously flawed in their firing solutions because their design criteria included only static and not dynamic operation. By 1943 an electronic director developed at Bell Labs superseded the M-7, which ceased production. A decade and a half of development at Sperry Gyroscope had not produced machines that could negotiate the fine line between performance and production imposed by the national emergency.

Still, Sperry's antiaircraft directors of the 1930s were early examples of technology that would assume a critical role in the 1940s. They also illustrate the subtle interplay between computation, human-machine interaction, and manufacturing. In Sperry's systems men were the glue that held integrated systems together. As human servomechanisms, they also acted as amplifiers, renewing the data so that they could make their way through complicated manipulations without losing accuracy. In this incarnation, the "computer" was neither the machine nor its human operators but rather the assemblage of the two. And technical decisions about how to represent the firing data in the machine had concrete effects for the industries required to produce it. When building the electronic and radar-controlled antiaircraft directors of World War II, engineers at Bell Labs, MIT, and elsewhere incorporated and built on Sperry Gyroscope's experience. They too grappled with feedback, control, and the augmentation of human capabilities by technical systems.

The Transition to War Production

In 1940 Sperry Gyroscope listed the following as its product line, along with the dates when the products were introduced:

Aircraft gyropilot (1931)
Automatic (radio) direction finder (1938)
Directional gyro (1918)
Gyro horizon (1930)
Incandescent searchlight (1924)
High-intensity searchlight (1916)
Course recorder (1918)
Ship gyropilot (1922)
Rudder indicator (1920)
Electromechanical steering system (1930)
Gyrocompass (1914)
Sound locator (1928)
Antiaircraft searchlight (1923)
Universal (antiaircraft) director (1936)[59]

All of these products, as well as the secret bombsights (not listed), were components of control systems. Only two were introduced after 1931. Despite Sperry Gyroscope's emphasis on new technology and its consistent engineering efforts, most of the company's catalog in 1940 did not represent important new inventions. The products had matured in the previous ten years, as had production methods, but antiaircraft fire control and bombsights represented the company's only significant new products in 1940. This stagnation reflects, in part, the effects of the Depression and the passing of Elmer Sperry. Also, several development programs also did not produce lasting products: Sperry naval fire control lost out to Ford and G.E., Sperry bombsights lost out to Norden, Sperry antiaircraft directors lost out to Bell Labs, and Sperry's aerial torpedoes and gyrostabilizers proved impracticable.

For every one of its product lines that stayed in production, Sperry tried several that failed; the company had great difficulty developing distributed, high-performance control systems and deploying them in the field. In fact, the company's history with automatic machinery is as remarkable for its difficulties as for its successes. The major prewar product line, antiaircraft fire control, was discontinued at the height of the wartime boom because of manufacturing complexities. Groups with no experience in fire control were able to learn the field quickly and build better systems than Sperry's. Still, during the 1930s, when military funding declined and government arsenals could not keep pace with new technology, Sperry sustained and developed control systems that otherwise would have stagnated. When the time came to ramp up production for war, the company was ready.

In 1940 the company introduced a number of new products that assured its success during the war. These included klystrons (oscillator tubes used in radar) developed by Russel and Sigurd Varian, whom Sperry supported, giving the company an advantage when radar growth exploded during World War II.[60] Sperry also excelled at simple, easily manufactured controls for fire control aboard aircraft. Unlike battleships, most World War II bombers did not use an airborne equivalent of director fire to coordinate their guns. The machine gunners who defended Flying Fortresses from attacking fighters worked individually, coordinating their fire through voice intercoms. Beginning in 1940 the Sperry Corporation produced these individual controls—as hydraulic turrets for machine gun defenses of B-24 and B-17 bombers. These devices allowed gunners to rapidly and smoothly swing their guns around to fend off attacking airplanes (and automatically prevented them from firing at parts of their own planes).

Sperry Gyroscope also built on its strength in aviation instruments and its corporate tradition, going back to the original gyrocompass, of reference and measuring devices. The company built instruments of perception. Gyroscopic sensors coupled to visual indicators called *lead-computing sights* imposed scales on the gunners' vision and indicated where to aim. "The automatic sight made possible by the simplicity and accuracy of its operation the training of more efficient gunners in shorter periods of time," the company wrote.[61] Vickers made the system's articulation component: small, electro-hydraulic power controls to move the turret. Subcontractors made the glass and steel structure.[62]

These machines, especially the famous ball turret, contributed to a popular image of mechanized air combat during World War II. Their production occupied much of Sperry's wartime resources (Fig. 3.15). At Sperry, at least, the vision of machines as "beast[s] of burden . . . obsessed with motion" survived. Only the B-29, operational late in the war, incorporated "central station" control of its defenses. Sperry Gyroscope developed a prototype of this system, but its design lost out to a G.E. design, partly

Image not available.

Fig. 3.15. Drawing by Alfred Crimi of an operator in a Sperry turret. The transparent body of the operator makes the machine controls visible. Courtesy of Hagley Museum and Library.

TABLE 3.1 Sperry Corporation Sales and R&D Expenses, 1933–1945

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because of Sperry's overburdened production lines.[63] During the war Sperry made, not the most advanced or intricate products, but rather those that effected simple, tight assemblages of mechanical and human functions and could be produced in large numbers. Even BuOrd needed these devices. As chapter 8 illustrates, Sperry sponsored a university researcher, Charles Stark Draper, to apply flight instruments to defending ships, and his work brought Sperry back into naval fire control after a twenty-year hiatus.

Close, human-centered controls produced great rewards for the Sperry Corporation when the company devoted itself exclusively to war production. Sperry Corporation sales doubled between 1941 and 1942, and they doubled again the following year. The company relied on subcontractors for more than a third of its work, in order to meet increases in production, and in 1942 sales peaked at 17 times the 1939 figures, equivalent to sales in the nine previous years combined (Table 3.1). The government built the company a $20 million plant measuring 1.35 million square feet at Lake Success on Long Island, which opened in early 1942, and by 1943 Sperry employed 50,000 people, ten times the 1939 number. The profits were so high that the company voluntarily returned money to the government.[64]

Conclusion: Survival of the Beast Vision

Elmer Sperry's greatest contribution may have been the very notion of a company that specialized in control systems as a discrete technology. Based on his vision, Sperry Gyroscope built a broad business stabilizing ships, guiding airplanes, and directing guns, all of which achieved higher performance than human operators could control unaided. The company rarely designed the machines themselves; rather, it added feedback loops to those designed elsewhere.

Sperry Gyroscope's control systems reined in machinery, adding precision to bring technological power into the range of human perception and reaction. Aboard ships, the company's controls closed a feedback loop between the gyrocompass and the ship's wheel, leaving the helmsman to adjust its parameters, monitor its performance, or exchange control, depending on the circumstances. In aircraft, Sperry established a similar feedback loop between gyroscopic instruments and the airplane's control surfaces. Here the human operator was a newer breed, and automatic controls extended pilots' range by reducing their fatigue. In both cases the military services valued the regularity the feedback loops provided, and Sperry built automated aiming systems around the stabilized vehicles. In antiaircraft fire control, the human operators became part of the feedback loops, amplifying and interpreting data at each stage in a complex computation. Each of these control systems called for different methods of representing the world, which had implications not only for the human operators but for manufacturing processes as well.

In 1942 the Sperry Corporation articulated the relationship between its unique approach to control systems, its organization of research, and the critical role of manufacturing:

> There has come into being a whole new field of scientific accessories to extend the functions and the skill of the operator far beyond his own strength, endurance, and abilities. . . . The importance to the Government of having these organizations [the Sperry companies] carrying on continuous research along these highly technical lines independent of governmental authority or even popular support is borne out

> by the fact that now the products of this twenty years of Sperry development must be produced in quantities much greater than the companies can handle.[65]

Sperry argued that its control systems made the critical link between the wartime mobilization of manpower and the mobilization of industry. "Over a billion dollars of this material [control systems] must be produced by us within the next two years. But this billion dollars' worth of technical equipment will fill the vital gap between the one hundred billion dollars' worth of weapons and the thousands of men who must operate them. Without this equipment, neither men nor weapons would be effective."[66] Sperry's control systems united the beasts procured by the military with the men who would ride them into battle.