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The History of Robotics

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1.1 The History of Robotics

The history of robotics is one that is highlighted by a fantasy world that has provided the inspiration to convert fantasy into reality. It is a history rich with cinematic creativity, scientific ingenuity, and entrepreneurial vision. Quite surprisingly, the definition of a robot is controversial, even among roboticists. At one end of the spectrum is the science fiction version of a robot, typically one of a human form — an android or humanoid — with anthropomorphic features. At the other end of the spectrum is the repetitive, efficient robot of industrial automation. In ISO 8373, the International Organization for Standardization defines a robot as "an automatically controlled, reprogrammable, multipurpose manipulator with three or more axes." The Robot Institute of America designates a robot as "a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks." A more inspiring definition is offered by Merriam-Webster, stating that a robot is "a machine that looks like a human being and performs various complex acts (as walking or talking) of a human being."

1.1.1 The Influence of Mythology

Mythology is filled with artificial beings across all cultures. According to Greek legend, after Cadmus founded the city of Thebes, he destroyed the dragon that had slain several of his companions; Cadmus then sowed the dragon teeth in the ground, from which a fierce army of armed men arose. Greek mythology also brings the story of Pygmalion, a lovesick sculptor, who carves a woman named Galatea out of ivory; after praying to Aphrodite, Pygmalion has his wish granted and his sculpture comes to life and becomes his bride. Hebrew mythology introduces the golem, a clay or stone statue, which is said to contain a scroll with religious or magic powers that animate it; the golem performs simple, repetitive tasks, but is difficult to stop. Inuit legend in Greenland tells of the Tupilaq, or Tupilak, which is a creature created from natural materials by the hands of those who practiced witchcraft; the Tupilaq is then sent to sea to destroy the enemies of the creator, but an adverse possibility existed — the Tupilaq can be turned on its creator if the enemy knows witchcraft. The homunculus, first introduced by 15th Century alchemist Paracelsus, refers to a small human form, no taller than 12 inches; originally ascribed to work associated with a golem, the homunculus became synonymous with an inner being, or the "little man" that controls the thoughts of a human. In 1818, Mary Wollstonecraft Shelley wrote *Frankenstein*, introducing the creature created by scientist Victor Frankenstein from various materials, including cadavers; Frankenstein's creation is grossly misunderstood, which leads to the tragic deaths of the scientist and many of the loved ones in his life. These mythological tales, and many like them, often have a common thread: the creators of the supernatural beings often see their creations turn on them, typically with tragic results.

1.1.2 The Influence of Motion Pictures

The advent of motion pictures brought to life many of these mythical creatures, as well as a seemingly endless supply of new artificial creatures. In 1926, Fritz's Lang's movie "Metropolis" introduced the first robot in a feature film. The 1951 film "The Day the Earth Stood Still" introduced the robot Gort and the humanoid alien Klaatu, who arrived in Washington, D.C., in their flying saucer. Robby, the Robot, first made his appearance in "Forbidden Planet" (1956), becoming one of the most influential robots in cinematic history. In 1966, the television show "Lost in Space" delivered the lovable robot B-9, who consistently saved the day, warning Will Robinson of aliens approaching. The 1968 movie "2001: A Space Odyssey" depicted a space mission gone awry, where Hal employed his artificial intelligence (AI) to wrest control of the space ship from the humans he was supposed to serve. In 1977, "Star Wars" brought to life two of the most endearing robots ever to visit the big screen — R2-D2 and C3PO. Movies and television have brought to life these robots, which have served in roles both evil and noble. Although just a small sampling, they illustrate mankind's fascination with mechanical creatures that exhibit intelligence that rivals, and often surpasses, that of their creators.

1.1.3 Inventions Leading to Robotics

The field of robotics has evolved over several millennia, without reference to the word *robot* until the early 20th Century. In 270 B.C., ancient Greek physicist and inventor Ctesibus of Alexandria created a water clock, called the clepsydra, or "water-thief," as it translates. Powered by rising water, the clepsydra employed a cord attached to a float and stretched across a pulley to track time. Apparently, the contraption entertained many who watched it passing away the time, or stealing their time, thus earning its namesake. Born in Lyon, France, Joseph Jacquard (1752–1834) inherited his father's small weaving business but eventually went bankrupt. Following this failure, he worked to restore a loom and in the process developed a strong interest in mechanizing the manufacture of silk. After a hiatus in which he served for the Republicans in the French Revolution, Jacquard returned to his experimentation and in 1801 invented a loom that used a series of punched cards to control the repetition of patterns used to weave cloths and carpets. Jacquard's card system was later adapted by Charles Babbage in early 19th Century Britain to create an automatic calculator, the principles of which later led to the development of computers and computer programming. The inventor of the automatic rifle, Christopher Miner Spencer (1833–1922) of Manchester, Connecticut, is also credited with giving birth to the screw machine industry. In 1873, Spencer was granted a patent for the lathe that he developed, which included a camshaft and a self-advancing turret. Spencer's turret lathe took the manufacture of screws to a higher level of sophistication by automating the process. In 1892, Seward Babbitt introduced a motorized crane that used a mechanical gripper to remove ingots from a furnace, 70 years prior to General Motors' first industrial robot used for a similar purpose. In the 1890s Nikola Tesla — known for his discoveries in AC electric power, the radio, induction motors, and more — invented the first remote-controlled vehicle, a radio-controlled boat. Tesla was issued Patent #613.809 on November 8, 1898, for this discovery.

1.1.4 First Use of the Word *Robot*

The word *robot* was not even in the vocabulary of industrialists, let alone science fiction writers, until the 1920s. In 1920, Karel Čapek (1890–1938) wrote the play, *Rossum's Universal Robots*, commonly known as *R.U.R.*, which premiered in Prague in 1921, played in London in 1921, in New York in 1922, and was published in English in 1923. Čapek was born in 1890 in Malé Svatonovice, Bohemia, Austria-Hungary, now part of the Czech Republic. Following the First World War, his writings began to take on a strong political tone, with essays on Nazism, racism, and democracy under crisis in Europe.

In *R.U.R.*, Čapek's theme is one of futuristic man-made workers, created to automate the work of humans, thus alleviating their burden. As Čapek wrote his play, he turned to his older brother, Josef, for a name to call these beings. Josef replied with a word he coined — *robot*. The Czech word *robotnik* refers to a peasant or serf, while *robota* means drudgery or servitude. The Robots (always capitalized by Čapek) are produced on a remote island by a company founded by the father-son team of Old Rossum and Young Rossum, who do not actually appear in the play. The mad inventor, Old Rossum, had devised the plan to create the perfect being to assume the role of the Creator, while Young Rossum viewed the Robots as business assets in an increasingly industrialized world. Made of organic matter, the Robots are created to be efficient, inexpensive beings that remember everything and think of nothing original. Domin, one of the protagonists, points out that because of these Robot qualities, "They'd make fine university professors." Wars break out between humans and Robots, with the latter emerging victorious, but the formula that the Robots need to create more Robots is burned. Instead, the Robots discover love and eliminate the need for the formula.

The world of robotics has Karel and Josef Čapek to thank for the word *robot*, which replaced the previously used *automaton*. Karel Čapek's achievements extend well beyond *R.U.R.*, including "War With The Newts," an entertaining satire that takes jabs at many movements, such as Nazism, communism, and capitalism; a biography of the first Czechoslovak Republic president, Tomáš Masaryk; numerous short stories, poems, plays, and political essays; and his famous suppressed text "Why I Am Not a Communist." Karel Čapek died of pneumonia in Prague on Christmas Day 1938. Josef Čapek was seized by the Nazis in 1939 and died at the Bergen-Belsen concentration camp in April 1945.

1.1.5 First Use of the Word *Robotics*

Isaac Asimov (1920–1992) proved to be another science fiction writer who had a profound impact on the history of robotics. Asimov's fascinating life began on January 2, 1920 in Petrovichi, Russia, where he was born to Jewish parents, who immigrated to America when he was three years old. Asimov grew up in Brooklyn, New York, where he developed a love of science fiction, reading comic books in his parents' candy store. He graduated from Columbia University in 1939 and earned a Ph.D. in 1948, also from Columbia. Asimov served on the faculty at Boston University, but is best known for his writings, which spanned a very broad spectrum, including science fiction, science for the layperson, and mysteries. His publications include entries in every major category of the Dewey Decimal System, except for Philosophy. Asimov's last nonfiction book, *Our Angry Earth*, published in 1991 and co-written with science fiction writer Frederik Pohl, tackles environmental issues that deeply affect society today — ozone depletion and global warming, among others. His most famous science fiction work, the *Foundation Trilogy*, begun in 1942, paints a picture of a future universe with a vast interstellar empire that experiences collapse and regeneration. Asimov's writing career divides roughly into three periods: science fiction from approximately 1940–1958, nonfiction the next quarter century, and science fiction again 1982–1992.

During Asimov's first period of science fiction writing, he contributed greatly to the creative thinking in the realm that would become robotics. Asimov wrote a series of short stories that involved robot themes. *I, Robot*, published in 1950, incorporated nine of these related short stories in one collection — "Robbie," "Runaround," "Reason," "Catch That Rabbit," "Liar!," "Little Lost Robot," "Escape!," "Evidence," and "The Evitable Conflict." It was in his short stories that Asimov introduced what would become the "Three Laws of Robotics." Although these three laws appeared throughout several writings, it was not until "Runaround," published in 1942, that they appeared together and in concise form. "Runaround" is also the first time that the word *robotics* is used, and it is taken to mean the technology dealing with the design, construction, and operation of robots. In 1985 he modified his list to include the so-called "Zeroth Law" to arrive at his famous "Three Laws of Robotics":

Zeroth Law: A robot may not injure humanity, or, through inaction, allow humanity to come to harm.

First Law: A robot may not injure a human being, or, through inaction, allow a human being to come to harm, unless this would violate a higher order law.

Second Law: A robot must obey the orders given to it by human beings, except where such orders would conflict with a higher order law.

Third Law: A robot must protect its own existence, as long as such protection does not conflict with a higher order law.

In "Runaround," a robot charged with the mission of mining selenium on the planet Mercury is found to have gone missing. When the humans investigate, they find that the robot has gone into a state of disobedience with two of the laws, which puts it into a state of equilibrium that sends it into an endless cycle of running around in circles, thus the name, "Runaround." Asimov originally credited John W. Campbell, long-time editor of the science fiction magazine *Astounding Science Fiction* (later renamed *Analog Science Fiction*), with the famous three laws, based on a conversation they had on December 23, 1940. Campbell declined the credit, claiming that Asimov already had these laws in his head, and he merely facilitated the explicit statement of them in writing.

A truly amazing figure of the 20th Century, Isaac Asimov wrote science fiction that profoundly influenced the world of science and engineering. In Asimov's posthumous autobiography, *It's Been a Good Life* (March 2002), his second wife, Janet Jeppson Asimov, reveals in the epilogue that his death on April 6, 1992, was a result of HIV contracted through a transfusion of tainted blood nine years prior during a triple-bypass operation. Isaac Asimov received over 100,000 letters throughout his life and personally answered over 90,000 of them. In *Yours, Isaac Asimov* (1995), Stanley Asimov, Isaac's younger brother, compiles 1,000 of these letters to provide a glimpse of the person behind the writings. A quote from one of those letters, dated September 20, 1973, perhaps best summarizes Isaac Asimov's career: "What I *will* be remembered for are the Foundation Trilogy and the Three Laws of Robotics. What I *want* to be remembered for is no one book, or no dozen books. Any single thing I have written can be paralleled or even surpassed by something someone else has done. However, my total corpus for quantity, quality, and *variety* can be duplicated by no one else. That is what I want to be remembered for."

1.1.6 The Birth of the Industrial Robot

Following World War II, America experienced a strong industrial push, reinvigorating the economy. Rapid advancement in technology drove this industrial wave — servos, digital logic, solid state electronics, etc. The merger of this technology and the world of science fiction came in the form of the vision of Joseph Engelberger, the ingenuity of George Devol, and their chance meeting in 1956. Joseph F. Engelberger was born on July 26, 1925, in New York City. Growing up, Engelberger developed a fascination for science fiction, especially that written by Isaac Asimov. Of particular interest in the science fiction world was the robot, which led him to pursue physics at Columbia University, where he earned both his bachelor's and master's degrees. Engelberger served in the U.S. Navy and later worked as a nuclear physicist in the aerospace industry.

In 1946, a creative inventor by the name of George C. Devol, Jr., patented a playback device used for controlling machines. The device used a magnetic process recorder to accomplish the control. Devol's drive toward automation led him to another invention in 1954, for which he applied for a patent, writing, "The present invention makes available for the first time a more or less general purpose machine that has universal application to a vast diversity of applications where cyclic control is desired." Devol had dubbed his invention *universal automation,* or *unimation* for short. Whether it was fate, chance, or just good luck, Devol and Engelberger met at a cocktail party in 1956. Their conversation revolved around robotics, automation, Asimov, and Devol's patent application, "A Programmed Article Transfer," which Engelberger's imagination translated into "robot." Following this chance meeting, Engelberger and Devol formed a partnership that lead to the birth of the industrial robot.

Engelberger took out a license under Devol's patent and bought out his employer, renaming the new company Consolidated Controls Corporation, based out of his garage. His team of engineers that had been working on aerospace and nuclear applications refocused their efforts on the development of the first industrial robot, named the Unimate, after Devol's "unimation." The first Unimate was born in 1961 and was delivered to General Motors in Trenton, New Jersey, where it unloaded high temperature parts from a die casting machine — a very unpopular job for manual labor. Also in 1961, patent number 2,998,237 was granted to Devol — the first U.S. robot patent. In 1962 with the backing of Consolidated Diesel Electric Company (Condec) and Pullman Corporation, Engelberger formed Unimation, Inc., which eventually blossomed into a prosperous business — GM alone had ordered 66 Unimates. Although it took until 1975 to turn a profit, Unimation became the world leader in robotics, with 1983 annual sales of $70 million and 25 percent of the world market share. For his visionary pursuit and entrepreneurship, Joseph Engelberger is widely considered the "Father of Robotics." Since 1977, the Robotic Industries Association has presented the annual Engelberger Robotics Awards to world leaders in both application and leadership in the field of robotics.

1.1.7 Robotics in Research Laboratories

The post-World War II technology boom brought a host of developments. In 1946 the world's first electronic digital computer emerged at the University of Pennsylvania at the hands of American scientists J. Presper Eckert and John Mauchly. Their computer, called ENIAC (electronic numerical integrator and computer), weighed over 30 tons. Just on the heels of ENIAC, Whirlwind was introduced by Jay Forrester and his research team at the Massachusetts Institute of Technology (MIT) as the first general purpose digital computer, originally commissioned by the U. S. Navy to develop a flight simulator to train its pilots. Although the simulator did not develop, a computer that shaped the path of business computers was born. Whirlwind was the first computer to perform real-time computations and to use a video display as an output device. At the same time as ENIAC and Whirlwind were making their appearance on the East Coast of the United States, a critical research center was formed on the West Coast.

In 1946, the Stanford Research Institute (SRI) was founded by a small group of business executives in conjunction with Stanford University. Located in Menlo Park, California, SRI's purpose was to serve as a center for technological innovation to support regional economic development. In 1966 the Artificial Intelligence Center (AIC) was founded at SRI, pioneering the field of artificial intelligence (AI), which gives computers the heuristics and algorithms to make decisions in complex situations.

From 1966 to 1972 Shakey, the Robot, was developed at the AIC by Dr. Charles Rosen (1917–2002) and his team. Shakey was the first mobile robot to reason its way about its surroundings and had a far-reaching influence on AI and robotics. Shakey was equipped with a television camera, a triangulating range finder, and bump sensors. It was connected by radio and video links to DEC PDP-10 and PDP-15 computers. Shakey was equipped with three levels of programming for perceiving, modeling, and interacting with its environment. The lowest level routines were designed for basic locomotion — movement, turning, and route planning. The intermediate level combined the low-level routines together to accomplish more difficult tasks. The highest-level routines were designed to generate and execute plans to accomplish tasks presented by a user. Although Shakey had been likened to a small unstable box on wheels — thus the name — it represented a significant milestone in AI and in developing a robot's ability to interact with its environment.

Beyond Shakey, SRI has advanced the field of robotics through contributions in machine vision, computer graphics, AI engineering tools, computer languages, autonomous robots, and more. A nonprofit organization, SRI disassociated itself from Stanford University in 1977, becoming SRI International. SRI's current efforts in robotics include advanced factory applications, field robotics, tactical mobile robots, and pipeline robots. Factory applications encompass robotic advances in assembly, parts feeding, parcel handling, and machine vision. In contrast to the ordered environment of manufacturing, field robotics involves robotic applications in highly unstructured settings, such as reconnaissance, surveillance, and explosive ordnance disposal. Similar to field robotics, tactical mobile robots are being developed for unstructured surroundings in both military and commercial applications, supplementing human capabilities, such as searching through debris following disasters (earthquakes, bombed buildings, etc.). SRI's pipeline robot, Magnetically Attached General Purpose Inspection Engine (MAGPIE), is designed to inspect natural gas pipelines, as small as 15 cm in diameter, for corrosion and leakage, navigating through pipe elbows and T-joints on its magnetic wheels.

In 1969 at Stanford University, a mechanical engineering student by the name of Victor Scheinman developed the Stanford Arm, a robot created exclusively for computer control. Working in the Stanford Artificial Intelligence Lab (SAIL), Scheinman built the entire robotic arm on campus, primarily using the shop facilities in the Chemistry Department. The kinematic configuration of the arm included six degrees of freedom with one prismatic and five revolute joints, with brakes on all joints to hold position while the computer computed the next position or performed other time-shared duties. The arm was loaded with DC electric motors, a harmonic drive, spur gear reducers, potentiometers, analog tachometers, electromechanical brakes, and a servo-controlled proportional electric gripper — a gripper with a 6-axis force/torque sensor in the wrist and tactile sense contacts on the fingers. The highly integrated Stanford Arm served for over 20 years in the robotics laboratories at Stanford University for both students and researchers.

The Stanford Cart, another project developed at SAIL, was a mobile robot that used an onboard television camera to navigate its way through its surroundings. The Cart was supported between 1973 and 1980 by the Defense Advanced Research Projects Agency (DARPA), the National Science Foundation (NSF), and the National Aeronautics and Space Administration (NASA). The cart used its TV camera and stereo vision routines to perceive the objects surrounding it. A computer program processed the images, mapping the obstacles around the cart. This map provided the means by which the cart planned its path. As it moved, the cart adjusted its plan according to the new images gathered by the camera. The system worked very reliably but was very slow; the cart moved at a rate of approximately one meter every 10 or 15 minutes. Triumphant in navigating itself through several 20-meter courses, the Stanford Cart provided the field of robotics with a reliable, mobile robot that successfully used vision to interact with its surroundings.

Research in robotics also found itself thriving on the U. S. East Coast at MIT. At the same time Asimov was writing his short stories on robots, MIT's Norbert Wiener published *Cybernetics, or the Control and Communication in the Animal and the Machine* (1948). In *Cybernetics* Wiener effectively communicates to both the trained scientist and the layman how feedback is used in technical applications, as well as everyday life. He skillfully brought to the forefront the sociological impact of technology and popularized the concept of control feedback.

Although artificial intelligence experienced its growth and major innovations in the laboratories of prestigious universities, its birth can be traced to Claude E. Shannon, a Bell Laboratories mathematician, who wrote two landmark papers in 1950 on the topic of chess playing by a machine. His works inspired John McCarthy, a young mathematician at Princeton University, who joined Shannon to organize a 1952 conference on automata. One of the participants at that conference was an aspiring Princeton graduate student in mathematics by the name of Marvin Minsky. In 1953 Shannon was joined by McCarthy and Minsky at Bell Labs. Creating an opportunity to rapidly advance the field of machine intelligence, McCarthy approached the Rockefeller Foundation with the support of Shannon. Warren Weaver and Robert S. Morison at the foundation provided additional guidance and in 1956 The Dartmouth Summer Research Project on Artificial Intelligence was organized at Dartmouth University, where McCarthy was an assistant professor of mathematics. Shannon, McCarthy, Minsky, and IBM's Nat Rochester joined forces to coordinate the conference, which gave birth to the term *artificial intelligence*.

In 1959 Minsky and McCarthy founded the MIT Artificial Intelligence Laboratory, which was the initiation of robotics at MIT (McCarthy later left MIT in 1963 to found the Stanford Artificial Intelligence Laboratory). Heinrich A. Ernst developed the Mechanical Hand-1 (MH-1), which was the first computer-controlled manipulator and hand. The MH-1 hand-arm combination had 35 degrees of freedom and was later simplified to improve its functionality. In 1968 Minsky developed a 12-joint robotic arm called the Tentacle Arm, named after its octopus-like motion. This arm was controlled by a PDP-6 computer, powered by hydraulics, and capable of lifting the weight of a person. Robot computer language development thrived at MIT as well: THI was developed by Ernst, LISP by McCarthy, and there were many other robot developments as well. In addition to these advancements, MIT significantly contributed to the field of robotics through research in compliant motion control, sensor development, robot motion planning, and task planning.

At Carnegie Mellon University, the Robotics Institute was founded in 1979. In that same year Hans P. Moravec took the principles behind Shakey at SRI to develop the CMU Rover, which employed three pairs of omni-directional wheels. An interesting feature of the Rover's kinematic motion was that it could open a door with its arm, travel a straight line through the doorway, rotating about its vertical axis to maintain the arm contact holding the door open. In 1993 CMU deployed Dante, an eight-legged rappelling robot, to descend into Mount Erebus, an active volcano in Antarctica. The intent of the mission was to collect gas samples and to explore harsh environments, such as those expected on other planets. After descending 20 feet into the crater, Dante's tether broke and Dante was lost. Not discouraged by the setback, in 1994 the Robotics Institute, led by John Bares and William "Red" Whittaker, sent a more robust Dante II into Mount Spurr, another active volcano 80 miles west of Anchorage, Alaska. Dante II's successful mission highlighted several major accomplishments: transmitting video, traversing rough terrain (for more than five days), sampling gases, operating remotely, and returning safely. Research at CMU's Robotics Institute continues to advance the field in speech understanding, industrial parts feeding, medical applications, grippers, sensors, controllers, and a host of other topics.

Beyond Stanford, MIT, and CMU, there are many more universities that have successfully undertaken research in the field of robotics. Now virtually every research institution has an active robotics research group, advancing robot technology in fundamentals, as well as applications that feed into industry, medicine, aerospace, military, and many more sectors.

1.1.8 Robotics in Industry

Running in parallel with the developments in research laboratories, the use of robotics in industry blossomed beyond the time of Engelberger and Devol's historic meeting. In 1959, Planet Corporation developed the first commercially available robot, which was controlled by limit switches and cams. The next year, Harry Johnson and Veljko Milenkovic of American Machine and Foundry, later known as AMF Corporation, developed a robot called Versatran, from the words *versatile transfer*; the Versatran became commercially available in 1963.

In Norway, a 1964 labor shortage led a wheelbarrow manufacturer to install the first Trallfa robot, which was used to paint the wheelbarrows. Trallfa robots, produced by Trallfa Nils Underhaug of Norway, were hydraulic robots with five or six degrees of freedom and were the first industrial robots to use the revolute coordinate system and continuous-path motion. In 1966, Trallfa introduced a spray-painting robot into factories in Byrne, Norway. This spray-painting robot was modified in 1976 by Ransome, Sims, and Jefferies, a British producer of agricultural machinery, for use in arc welding applications. Painting and welding developed into the most common applications of robots in industry.

Seeing success with their Unimates in New Jersey, General Motors used 26 Unimate robots to assemble the Chevrolet Vega automobile bodies in Lordstown, Ohio, beginning in 1969. GM became the first company to use machine vision in an industrial setting, installing the Consight system at their foundry in St. Catherines, Ontario, Canada, in 1970.

At the same time, Japanese manufacturers were making quantum leaps in manufacturing: cutting costs, reducing variation, and improving efficiency. One of the major factors contributing to this transformation was the incorporation of robots in the manufacturing process. Japan imported its first industrial robot in 1967, a Versatran from AMF. In 1971 the Japanese Industrial Robot Association (JIRA) was formed, providing encouragement from the government to incorporate robotics. This move helped to move the Japanese to the forefront in total number of robots used in the world. In 1972 Kawasaki installed a robot assembly line, composed of Unimation robots at their plant in Nissan, Japan. After purchasing the Unimate design from Unimation, Kawasaki improved the robot to create an arc-welding robot in 1974, used to fabricate their motorcycle frames. Also in 1974, Hitachi developed touch and force-sensing capabilities in their Hi-T-Hand robot, which enabled the robot to guide pins into holes at a rate of one second per pin.

At Cincinnati Milacron Corporation, Richard Hohn developed the robot called The Tomorrow Tool, or T^3. Released in 1973, the T^3 was the first commercially available industrial robot controlled by a microcomputer, as well as the first U.S. robot to use the revolute configuration. Hydraulically actuated, the T^3 was used in applications such as welding automobile bodies, transferring automobile bumpers, and loading machine tools. In 1975, the T^3 was introduced for drilling applications, and in the same year, the T^3 became the first robot to be used in the aerospace industry.

In 1970, Victor Scheinman, of Stanford Arm fame, left his position as professor at Stanford University to take his robot arm to industry. Four years later, Scheinman had developed a minicomputer-controlled robotic arm, known as the Vicarm, thus founding Vicarm, Inc. This arm design later came to be known as the "standard arm." Unimation purchased Vicarm in 1977, and later, relying on support from GM, used the technology from Vicarm to develop the PUMA (Programmable Universal Machine for Assembly), a relatively small electronic robot that ran on an LSI II computer.

The ASEA Group of Västerås, Sweeden, made significant advances in electric robots in the 1970's. To handle automated grinding operations, ASEA introduced its IRb 6 and IRb 60 all-electric robots in 1973. Two years later, ASEA became the first to install a robot in an iron foundry, tackling yet more industrial jobs that are not favored by manual labor. In 1977 ASEA introduced two more electric-powered industrial robots, both of which used microcomputers for programming and operation. Later, in 1988, ASEA merged with BBC Brown Boveri Ltd of Baden, Switzerland, to form ABB (ASEA, Brown, and Boveri), one of the world leaders in power and automation technology.

At Yamanashi University in Japan, IBM and Sankyo joined forces to develop the Selective Compliance Assembly Robot Arm (SCARA) in 1979. The SCARA was designed with revolute joints that had vertical axes, thus providing stiffness in the vertical direction. The gripper was controlled in compliant mode, or using force control, while the other joints were operated in position control mode. These robots were used and continue to be used in many applications where the robot is acting vertically on a workpiece oriented horizontally, such as polishing and insertion operations. Based on the SCARA geometry, Adept Technology was founded in 1983. Adept continues to supply direct drive robots that service industries, such as telecommunications, electronics, automotive, and pharmaceuticals. These industrial developments in robotics, coupled with the advancements in the research laboratories, have profoundly affected robotics in different sectors of the technical world.

1.1.9 Space Exploration

Space exploration has been revolutionized by the introduction of robotics, taking shape in many different forms, such as flyby probes, landers, rovers, atmospheric probes, and robot arms. All can be remotely operated and have had a common theme of removing mankind from difficult or impossible settings. It would not be possible to send astronauts to remote planets and return them safely. Instead, robots are sent on these journeys, transmitting information back to Earth, with no intent of returning home.

Venus was the first planet to be reached by a space probe when Mariner 2 passed within 34,400 kilometers in 1962. Mariner 2 transmitted information back to earth about the Venus atmosphere, surface temperature, and rotational period. In December 1970, Venera 7, a Soviet lander, became the first man-made object to transmit data back to Earth after landing on another planet. Extreme temperatures limited transmissions from Venera 7 to less than an hour, but a new milestone had been achieved. The Soviets' Venera 13 became the first lander to transmit color pictures from the surface of Venus when it landed in March 1982. Venera 13 also took surface samples by means of mechanical drilling and transmitted analysis data via the orbiting bus that had dropped the lander. Venera 13 survived for 127 minutes at 236°C (457°F) and 84 Earth atmospheres, well beyond its design life of 32 minutes. In December 1978, NASA's Pioneer Venus sent an Orbiter into an orbit of Venus, collecting information on Venusian solar winds, radar images of the surface, and details about the upper atmosphere and ionosphere. In August 1990, NASA's Magellan entered the Venus atmosphere, where it spent four years in orbit, radar-mapping 98% of the planet's surface before plunging into the dense atmosphere on October 11, 1994.

NASA's Mariner 10 was the first space probe to visit Mercury and was also the first to visit two planets — Venus and Mercury. Mariner 10 actually used the gravitational pull of Venus to throw it into a different orbit, where it was able to pass Mercury three times between 1974 and 1975. Passing within 203 kilometers of Mercury, the probe took over 2800 photographs to detail a surface that had previously been a mystery due to the Sun's solar glare that usually obscured astronomers' views.

The red planet, Mars, has seen much activity from NASA spacecraft. After several probe and orbiter missions to Mars, NASA launched Viking 1 and Viking 2 in August and September of 1975, respectively. The twin spacecraft, equipped with robotic arms, began orbiting Mars less than a year later, Viking 1 in June 1976 and Viking 2 in August 1976. In July and September of the same year, the two landers were successfully sent to the surface of Mars, while the orbiters remained in orbit. The Viking orbiters 1 and 2 continued transmission to Earth until 1980 and 1978, respectively, while their respective landers transmitted data until 1982 and 1980. The successes of this mission were great: Viking 1 and 2 were the first two spacecraft to land on a planet and transmit data back to Earth for an extended period; they took extensive photographs; and they conducted biological experiments to test for signs of organic matter on the red planet. In December 1996, the Mars Pathfinder was launched, including both a lander and a rover, which arrived on Mars in July of 1997. The lander was named the Carl Sagan Memorial Station, and the rover was named Sojourner after civil rights crusader Sojourner Truth. Both the lander and rover outlived their design lives, by three and 12 times, with final transmissions coming in late September 1997. In mid-2003, NASA launched its Mars Exploration Rovers mission with twin rovers, Spirit and Opportunity, which touched down in early and late January 2004, respectively. With greater sophistication and better mobility than Sojourner, these rovers landed at different locations on Mars, each looking for signs of liquid water that might have existed in Mars' past. The rovers are equipped with equipment — a panoramic camera, spectrometers, and a microscopic imager — to capture photographic images and analyze rock and soil samples.

Additional missions have explored the outer planets — Jupiter, Saturn, Uranus, and Neptune. Pioneer 10 was able to penetrate the asteroid belt between Mars and Jupiter to transmit close-up pictures of Jupiter, measure the temperature of its atmosphere, and map its magnetic field. Similarly, Pioneer 11 transmitted the first close-up images of Saturn and its moon Titan in 1979. The Voyager missions followed closely after Pioneer, with Voyager 2 providing close-up analysis of Uranus, revealing 11 rings around the planet, rather than the previously thought nine rings. Following its visit to Uranus, Voyager 2 continued to Neptune, completing its 12-year journey through the solar system. Galileo was launched in 1989 to examine Jupiter and its four largest moons, revealing information about Jupiter's big red spot and about the moons Europa and Io. In 1997, NASA launched the Cassini probe on a seven-year journey to Saturn, expecting to gather information about Saturn's rings and its moons.

The International Space Station (ISS), coordinated by Boeing and involving nations from around the globe, is the largest and most expensive space mission ever undertaken. The mission began in 1995 with U.S. astronauts, delivered by NASA's Space Shuttle, spending time aboard the Russian Mir space station. In 2001, the Space Station Remote Manipulator System (SSRMS), built by MD Robotics of Canada, was successfully launched to complete the assembly operations of the ISS. Once completed, the ISS research laboratories will explore microgravity, life science, space science, Earth science, engineering research and technology, and space product development.

1.1.10 Military and Law Enforcement Applications

Just as space programs have used robots to accomplish tasks that would not even be considered as a manned mission, military and law enforcement agencies have employed the use of robots to remove humans from harm's way. Police are able to send a microphone or camera into a dangerous area that is not accessible to law enforcement personnel, or is too perilous to enter. Military applications have grown and continue to do so.

Rather than send a soldier into the field to sweep for landmines, it is possible to send a robot to do the same. Research is presently underway to mimic the method used by humans to identify landmines. Another approach uses swarm intelligence, which is research being developed at a company named Icosystems, under funding from DARPA. The general approach is similar to that of a colony of ants finding the most efficient path through trial and error, finding success based on shear numbers. Icosystems is using 120 robots built by I-Robot, a company co-founded by robotics pioneer Rodney Brooks, who is also the director of the Computer Science and Artificial Intelligence Laboratory at MIT. One of Brooks' research interests is developing intelligent robots that can operate in unstructured environments, an application quite different from that in a highly structured manufacturing environment.

Following the tragic events of September 11, 2001, the United States retaliated against al Qaeda and Taliban forces in Afghanistan. One of the weapons that received a great deal of media attention was the Predator UAV (unmanned aerial vehicle), or drone. The drone is a plane that is operated remotely with no human pilot on-board, flying high above an area to collect military intelligence. Drones had been used by the U.S. in the Balkans in 1999 in this reconnaissance capacity, but it was during the engagement in Afghanistan that the drones were armed with anti-tank missiles. In November 2002, a Predator UAV fired a Hellfire missile to destroy a car carrying six suspected al Qaeda operatives. This strike marked a milestone in the use of robotics in military settings.

Current research at Sandia National Laboratory's Intelligent Systems and Robotics Center is aimed at developing robotic sentries, under funding from DARPA. These robots would monitor the perimeter of a secured area, signaling home base in the event of a breach in security. The technology is also being extended to develop ground reconnaissance vehicles, a land version of the UAV drones.

1.1.11 Medical Applications

The past two decades have seen the incorporation of robotics into medicine. From a manufacturing perspective, robots have been used in pharmaceuticals, preparing medications. But on more novel levels, robots have been used in service roles, surgery, and prosthetics.

In 1984 Joseph Engelberger formed Transition Research Corporation, later renamed HelpMate Robotics, Inc., based in Danbury, Connecticut. This move by Engelberger marked a determined effort on his part to move robotics actively into the service sector of society. The first HelpMate robot went to work in a Danbury hospital in 1988, navigating the hospital wards, delivering supplies and medications, as needed by hospital staff.

The capability of high-precision operation in manufacturing settings gave the medical industry high hopes that robots could be used to assist in surgery. Not only are robots capable of much higher precision than a human, they are not susceptible to human factors, such as trembling and sneezing, that are undesirable in the surgery room. In 1990, Robodoc was developed by Dr. William Bargar, an orthopedist, and the late Howard Paul, a veterinarian, of Integrated Surgical Systems, Inc., in conjunction with the University of California at Davis. The device was used to perform a hip replacement on a dog in 1990 and on the first human in 1992, receiving U.S. Food and Drug Administration (FDA) approval soon thereafter. The essence of the procedure is that traditional hip replacements required a surgeon to dig a channel down the patient's femur to allow the replacement hip to be attached, where it is cemented in place. The cement often breaks down over time, requiring a new hip replacement in 10 or 15 years for many patients. Robodoc allows the surgeon to machine a precise channel down the femur, allowing for a tight-fit between replacement hip and femur. No cement is required, allowing the bone to graft itself onto the bone, creating a much stronger and more permanent joint.

Another advantage to robots in medicine is the ability to perform surgery with very small incisions, which results in minimal scar tissue, and dramatically reduced recovery times. The popularity of these minimally invasive surgical (MIS) procedures has enabled the incorporation of robots in endoscopic surgeries. Endoscopy involves the feeding of a tiny fiber optic camera through a small incision in the patient. The camera allows the surgeon to operate with surgical instruments, also inserted through small incisions, avoiding the trauma of large, open cuts. Endoscopic surgery in the abdominal area is referred to as laparoscopy, which has been used since the late 1980's for surgery on the gall bladder and female organs, among others. Thorascopic surgery is endoscopic surgery inside the chest cavity — lungs, esophagus, and thoracic artery. Robotic surgical systems allow doctors to sit at a console, maneuvering the camera and surgical instruments by moving joysticks, similar to those used in video games. This same remote robotic surgery has been extended to heart surgery as well. In addition to the precision and minimized incisions, the robotic systems have an advantage over the traditional endoscopic procedure in that the robotic surgery is very intuitive. Doctors trained in endoscopic surgery must learn to move in the opposite direction of the image transmitted by the camera, while the robotic systems directly mimic the doctor's movements. As of 2001, the FDA had cleared two robotic endoscopic systems to perform both laparoscopic and thoracoscopic surgeries — the da Vinci Surgical System and the ZEUS Robotic Surgical System.

Another medical arena that has shown recent success is prosthetics. Robotic limbs have been developed to replicate natural human movement and return functionality to amputees. One such example is a bionic arm that was developed at the Princess Margaret Rose Hospital in Edinburgh, Scotland, by a team of bioengineers, headed by managing director David Gow. Conjuring up images of the popular 1970's television show "The Six Million Dollar Man," this robotic prosthesis, known as the Edinburgh Modular Arm System (EMAS), was created to replace the right arm from the shoulder down for Campbell Aird, a man whose arm was amputated after finding out he had cancer. The bionic arm was equipped with a motorized shoulder, rotating wrist, movable fingers, and artificial skin. With only several isolated glitches, the EMAS was considered a success, so much so that Aird had taken up a hobby of flying.

Another medical frontier in robotics is that of robo-therapy. Research at NASA's Jet Propulsion Laboratory (JPL) and the University of California at Los Angeles (UCLA) has focused on using robots to assist in retraining the central nervous system in paralyzed patients. The therapy originated in Germany, where researchers retrained patients through a very manually intensive process, requiring four or more therapists. The new device would take the place of the manual effort of the therapists with one therapist controlling the robot via hand movements inside a set of gloves equipped with sensors.

1.1.12 Other Applications and Frontiers of Robotics

In addition to their extensive application in manufacturing, space exploration, the military, and medicine, robotics can be found in a host of other fields, such as the ever-present entertainment market — toys, movies, etc. In 1998 two popular robotic toys came to market. Tiger Electronics introduced "Furby" which rapidly became the toy of choice in the 1998 Christmas toy market. Furby used a variety of different sensors to react with its environment, including speech that included over 800 English phrases, as well as many in its own language "Furbish." In the same year Lego released its Lego MINDSTORMS robotic toys. These reconfigurable toys rapidly found their way into educational programs for their value in engaging students, while teaching them about the use of multiple sensors and actuators to respond to the robot's surroundings. Sony released a robotic pet named AIBO in 1999, followed by the third generation AIBO ERS-7 in 2003. Honda began a research effort in 1986 to build a robot that would interact peacefully with humans, yielding their humanoid robots P3 in 1996 and ASIMO in 2000 (ASIMO even rang the opening bell to the New York Stock Exchange in 2002 to celebrate Honda's 25 years on the NYSE). Hollywood has maintained a steady supply of robots over the years, and there appears to be no shortage of robots on the big screen in the near future.

Just as Dante II proved volcanic exploration possible, and repeated NASA missions have proven space exploration achievable, deep sea explorers have become very interested in robotic applications. MIT researchers developed the Odyssey IIb submersible robot for just such exploration. Similar to military and law enforcement robotic applications of bomb defusing and disposal, nuclear waste disposal is an excellent role for robots to fill, again, removing their human counterparts from a hazardous environment. An increasing area of robotic application is in natural disaster recovery, such as fallen buildings and collapsed mines. Robots can be used to perform reconnaissance, as well as deliver life-supporting supplies to trapped personnel.

Looking forward there are many frontiers in robotics. Many of the applications presented here are in their infancy and will see considerable growth. Other mature areas will see sustained development, as has been the case since the technological boom following the Second World War. Many theoretical areas hold endless possibilities for expansion — nonlinear control, computational algebra, computational geometry, intelligence in unstructured environments, and many more. The possibilities seem even more expansive when one considers the creativity generated by the cross-pollination of playwrights, science fiction writers, inventors, entrepreneurs, and engineers.