Tracking the PUMA

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Marsh paper
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David Noble's *Forces of Production* is the standard account of factory automation. Noble looks at machine tools "because they are the guts of modern industry" and automation "because it is the hallmark of twentieth-century manufacturing."[1] Focusing on the development of numerical control (N/C) of machine tools in the 1950s, he argues that automation resulted in the deskilling of shop floor workers while engineers took control of workers' tacit knowledge by implementing computer programming of the machines. Moving the story twenty years into the future and looking at the automation of light assembly work using robots (areas untouched by Noble), a story emerges that has common roots with the development of N/C machine tools, but with a different outcome.

The PUMA, or Programmable Universal Machine (Manipulator) for Assembly, was the first human-scale, electric robot designed for lightweight assembly.[2] It represented a change from heavy, hydraulic, single use machines to lightweight, electric, multi-programmable machines. Framing the story of factory automation around the PUMA raises questions, such as: What is the role of a prototype in introducing management to possible applications? How does management use a prototype to educate workers while allaying their fears of replacement? How is knowledge created and disseminated when working with a new technology? Who controls that knowledge? Why does a technology fail, and how does it succeed in unexpected places? The story of the PUMA is not a story of deskilling factory workers and engineers' quest for control. It is a story of a break through technology that emerged from the academic community to be pioneered by a group of research engineers at General Motors. The PUMA failed to revolutionize lightweight assembly work because the engineers who developed it were isolated from mainstream production work and because the technology was not sufficient to support a sophisticated system. Despite its failures in industry, the PUMA returned to universities and is used to teach robotics applications, which has brought together the electrical, mechanical, and computer engineering disciplines.

[1] David Noble, *Forces of Production: A Social History of Industrial Automation,* (Oxford University Press: New York, 1984), p. xii.
[2] The name PUMA was coined by GM during the initial speculations on the possibilities of an assembly line robot.

A Brief History of Robotics

In 1922 Czech playwright Karel Capek wrote *R.U.R.*, or *Rosum's Universal Robots*, and the 1923 translation brought the word "robot" into the English language from the Czech word for worker. Although the history of robots can be linked to the automata of the 18th century just as computers are linked to Babbage's Difference Engine, the first modern industrial robot dates from 1954 when George DeVol filed a patent for a general-purpose manipulator. Two years after filing his patent, DeVol met Joseph Engelberger, a physicist working in aeronautical engineering, at what the robotics literature refers to as "the famous cocktail party." As the party progressed, DeVol and Engelberger planned to build flexible machines for factory automation.[3] Flexible automation was the novelty of their discussion and the basis of robotics. When Ford executive Del Harder coined the term "automation" in 1947, he was describing the increased use of "electro-mechanical, hydraulic, and pneumatic special-purpose production and parts-handling machinery."[4] What he and historians such as Noble were describing was fixed automation, where machines are dedicated to a particular task. Robotics represented a new opportunity for flexible automation because they could be programmed and relocated to perform a variety functions.

DeVol eventually sold his patents to Condec, a company headed by Engelberger that became Unimation.[5] In 1972 Unimation became the first company to dedicate its manufacturing solely to robots.[6] Its foundational product was the Unimate, a "hydraulically powered, mechanically actuated arm, with a pneumatically operated hand." [7] Unimation sold its first

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[3] Peter B. Scott. *The Robotics Revolution: The Complete Guide for Managers and Engineers.* (Basil Blackwell, Inc.: New York, 1984.) p. 29.
[4] Noble, p. 66.
[5] The name is coined from the combination of universal automation.
[6] Scott, p. 30.
[7] Floyd Holroyd, *Industrial Robots,* an internal document compiled for the Mechanical Engineering Department of GM Manufacturing Development, February 1972. p 5.

Unimate to General Motors. The Unimate was GM's most popular, but also most expensive, robot on the floor in 1972, with costs running in the range of $30-35, 000. [8]

GM's use of robots on the shop floor dates from 1961 when it commissioned its first industrial robot, a die cast unload, in the Ternstedt plant in Trenton, NJ.[9] This early application of a robot fits the pattern of automating the dirty, dreary, and dangerous jobs first. The robot took over the tedious job of standing next to the hot machine and removing the finished castings. In 1967 GM installed the first two spot welding robots at its Norwood plant without much controversy, but when they launched the first spot welding line of 28 robots in 1970 at the Lordstown, OH plant, workers began to protest.[10]

The Lordstown, OH plant is often singled out as a case study for factory workers revolting against automation. GM chose Lordstown to produce its first subcompact car, the Chevrolet Vega, and retooled the plant to increase efficiency. In 1971 General Motors Assembly Division (GMAD) instituted efficiency studies that resulted in the dismissal of 700 workers, the reassignment of hundreds more, and the elimination of 300-500 line jobs considered too easy for human workers. They increased line speeds from 60 to 101 cars per hour, producing nearly 400,000 Vegas in 1972. To meet production quotas, workers had mandatory overtime with shifts running eleven to twelve hours and including weekend work. When workers protested, supervisors reacted by firing and laying off the most militant workers. Workers filed over

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[8] Ibid.
[9] "Robotics History & GM" *Historical Documents Related to the PUMA Robot Development Compiled for the General Motors Corporation Donation of the Original PUMA Prototype Robot "Alice" to the Smithsonian Institution.* Compiled by Steven W. Holland. April 19, 2002.
[10] Ibid.

16,000 grievances and then began staging strikes, blocking the front gates, and threatening supervisors. In March of 1972, a strike completely shut down the plant for 22 days.[11]

Despite the problems at Lordstown, GM continued to explore possibilities for robots. In 1972 the Mechanical Engineering Department in Manufacturing Development surveyed the use of robots at GM and found more than 100 first generation robots in active use, with over sixty of them being welding robots.[12] The robotics initiatives from GM's different divisions were combined in 1974 with the establishment of a central robot lab in the Manufacturing Development division.[13]

Outside of industry, students at major research universities were attempting to incorporate robotics into the curriculum. However, academic environments were slow to embrace the interdisciplinary nature of robotics. Stanford and MIT were the first universities to have dedicated robotics labs, but even there students often had to negotiate their own paths across multiple departments. It was in this academic environment that the physical robot that became the PUMA was born.

Engineering on the Outskirts

From the PUMA's inception at Stanford University to its implementation at General Motors, the engineers who developed the PUMA worked outside the traditional engineering disciplines. Vic Scheinman, a graduate student at Stanford and inventor of the Vicarm (which later became the PUMA), used resources in three different departments to design and build his prototype. Mitch Weiss, the lead applications engineer on the PUMA at Unimation Inc.,

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[11] James M. Rubenstein, *The Changing US Auto Industry: A Geographical Analysis.* (Routledge: New York, 1992.) Almost all of the literature on automation at least mentions Lordstown, and there is much literature dedicated solely to Lordstown, especially within labor history studies.
[12] *Industrial Robots.* p. 2.

designed his own curriculum while at MIT and inherited the PUMA project at Unimation after his supervisor abandoned it. The team that pioneered the PUMA at GM came together through a combination of curiosity in robotics and a lack of clear direction or support from top-level supervisors. Working outside their traditional academic or corporate divisions gave the PUMA developers autonomy and freedom to design this break-through technology.

Vic Scheinman initially conceived his robot arm as his master's thesis in the Mechanical Engineering department at Stanford University. His funding was through a research assistantship in the Computer Science department's artificial intelligence lab, but he machined his first robot prototype at night in the Chemistry department's machine shop. There was no department, not even an interdisciplinary program, to support Scheinman's research. Instead, he had to carve out his own space on the intersecting boundaries of traditional departments.

The atmosphere at MIT was similar. Mitch Weiss, who became the lead applications engineer for PUMA projects at Unimation, knew he wanted to pursue a career in robotics after graduating, but he found the curriculum too rigid. He received permission to design his own curriculum, half electrical engineering courses and half mechanical engineering courses with additional work in the AI lab. However, the freedom to design his own curriculum came with a typical warning from his advisor that although it was a noble intellectual pursuit, he would never find a job with that background.[14]

Weiss proved his advisor wrong when Unimation Inc., the leading manufacturer of industrial robots, hired him. Weiss was assigned as a trainee to an applications engineer on the newly acquired PUMA project. Many of the engineers at Unimation, including Weiss's

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[13] "Robotics History & GM"

[14] On April 19, 2002, the National Museum of American History hosted a videotaped session of panel interviews with the developers of the PUMA. I transcribed these videotapes, and information from these interviews will be referenced as videohistory transcript.

supervisor, did not want to work with engineers from MIT because MIT graduates were not considered to have any practical engineering knowledge. Many of Unimation's engineers also had no interest in working on the PUMA because it was considered risky to work on an assembly line prototype; there was steady work and much more money in Unimation's hydraulic spot welding robots. Weiss inherited the PUMA with almost total autonomy; his supervisor abandoned him on his first day.[15]

Joel Engelberger served as the PUMA's bridge between university and industrial research labs. Engelberger first met Scheinman at a robotics convention when Scheinman was literally outside the robotics field. Scheinman was sitting on the steps outside the convention center demonstrating his small robot arm to a crowd of onlookers. Engelberger, impressed and intrigued, offered Scheinman a small corner of a table in Unimation's large booth. Scheinman established a small company and marketed his robot arm as the Vicarm, but he soon realized that he preferred research and development to selling his finished product. Scheinman worked closely with Engelberger to shape the prototype Vicarm to match GM's specifications, but he eventually sold the rights to the Vicarm to Unimation. Unimation renamed the Vicarm and marketed it under the trademarked name PUMA.[16] Because of Engelberger's established business ties with GM and his appreciation of Scheinman's innovation, Engelberger was able to coordinate the project that brought a design from the academic environment into an industrial research lab.

Despite the establishment of a dedicated robotics center, research at GM was not always coordinated. Both Manufacturing Development and Research Laboratories, two separate divisions within GM, were experimenting with robotics, but there was no cross-divisional

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[15] Ibid.
[16] Ibid.

communications. During the late 1960s GM began a massive reorganization of the domestic company. Stemming from a decline in the rate of profits, GM attempted to reduce redundancies in design, production, and inventory and to reduce operating costs by centralizing control over manufacturing. Beginning in 1968, it stripped divisions of much of their control over engineering and assembly, which was transferred to the new division GMAD. GM adopted the "project centers" model for new design work, where engineers and designers from the various divisions would temporarily meet to collaborate on the basic platforms for GM's model lines. The project centers would coordinate the necessary modifications for each division, but when the design process was complete, the project centers were disbanded.[17]

The goal of GMAD was to create a centralized "coordinated engineering" program with each division responsible for the development of a specific system for all GM cars. For example, Oldsmobile developed steering systems while Buick worked on brakes. There was a push to standardize parts and engines among the various model lines in order to reduce overall inventory.[18] Theoretically, this would simplify assembly. However, GMAD focused on the large-scale assembly processes, for example, hanging fenders onto chasses and installing the engines. At the time, almost no one at GM was concerned with automating light assembly. The exceptions were Floyd Holroyd and Dick Beecher, who came to be the lead project engineers for the PUMA.

Floyd Holroyd came out of the Mechanical Engineering Department of the Manufacturing Development Division. His supervisor was curious about robot implementations at GM, and Holroyd was given the task of surveying the commercially available industrial robots, seeing how robots were used at GM, and locating possible applications for additional

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[17] Carl H. A. Dassbach, *Global Enterprises and the World Economy: Ford, General Motors, and IBM, the Emergence of the Transnational Enterprise.* (Garland Publishing, Inc.: New York, 1989) pp. 433-439.

robot use at GM.[19] At the same time in a different department, Beecher was casting about for a assembly project. Beecher was part of the newly formed Assembly Processing and Material Handling department, where he had been given a title and the freedom to invent his job description. Both Holroyd and Beecher realized that contrary to GMAD's focus, the bulk of automotive assembly was not in the large-scale processes, but rather in light assembly work. In an automobile, roughly 90% of the parts to be assembled weigh less than five pounds.[20] Approximately 89,000 employees' jobs at General Motors were classified as light-assembly.

Holroyd and Beecher realized the potential of robotic use in light assembly and began collaborating on the PUMA project.[21] From the beginning they were navigating uncharted waters. Not only was GM not automating light assembly, but Holroyd's 1972 survey of industrial robots also showed no companies producing robots on a scale capable of light assembly work. For his *Industrial Robots* survey, Holroyd collected trade literature from the robot manufacturers with US distributors. It included eleven companies from the US, one from England, and three from Japan. All of the robots marketed were for use in stamping, casting, and other heavy machinery applications.[22] Holroyd's first request for proposals was not a refined list of performance specifications. Rather, it was a wish list to spark a dialog between GM and potential manufactures to produce a viable robot. Holroyd was virtually ignored by the robot industry; companies were not seriously considering a request for electric robots at this time. One perspective company requested a two-year feasibility study before taking additional actions.

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[18] Ibid.
[19] Videohistory transcript. Holroyd compiled his report, *Industrial Robots,* and circulated it throughout GM in February 1972.
[20] This commonly quoted figure varies from 90 to 95% of parts weigh less than 3 to 5 pounds.
[21] Floyd Holroyd and Walt Cwcyshyn were transferred from Mechanical Engineering to Dick Beecher's department when the Mechanical Engineering supervisor (who had initiated Holroyd's robot search) found out they were engaging in industrial engineering activities.

Unimation was the only company that responded favorably to GM's request, most likely because Engelberger already envisioned the possibilities of adapting Scheinman's robot.

Selling the PUMA on the Shop Floor

Beecher and Holroyd operated in a semi-autonomous research lab within GM, which allowed them to test and modify the PUMA before implementing it on an assembly line. The new project centers structure gave them freedom to develop their ideas, but did not give them an obvious end client. Manufacturing Development's customers were the producing divisions of General Motors. If the divisions were not satisfied with MD's products, they did not have to implement the developments. As a result, Beecher and Holroyd needed to convince the different divisions of GM of the possibilities of adding robots.

Beecher and Holroyd attempted to sell the idea of the PUMA as a friendly co-worker and began by introducing the PUMA in innocuous settings. At one annual meeting, they had the PUMA handing out programs to participants.[23] The PUMA also made a guest appearance on the Merv Griffin Show where it watered flowers. Most importantly, Beecher and Holroyd had an open door policy at their lab. They regularly offered tours to employees to show off their latest developments.

One of the most distinctive features of the PUMA is that it was built on a human scale. The robot arm is in proportion to a human arm; its six degrees of freedom mirrors human motion, roughly comparable to the human motions at the waist, shoulder, elbow, wrist, and hand. It worked at a similar pace to human assemblers; and it occupied roughly the same space as a

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[22] Holroyd's report included a summary of his findings plus samples of trade literature from all of the manufacturers listed. Whenever the Smithsonian collects an object they try to include accompanying trade literature to position the object within the context of the field.
[23] Videohistory transcript.

worker on a small parts line.[24] This human scale design was used as a selling point when attempting to convince foremen to accept robots. Knowing full well the frailties of the early automated systems, Walt Cwcyshyn argued for the PUMA by saying, "if it doesn't work, pull it out, park it to the side, repair it, put a person in there. It's the same size; it'll do the same thing."[25] Perhaps with Lordstown in mind, foremen did not increase the speed of the human-robot assembly line.[26] Although the PUMA could work three times as fast as a human assembler, the foremen wanted to be able to replace the PUMA with a human without changing anything, including speed, on the assembly line.[27]

Although human scale was an essential design feature, during implementation the PUMA designers stressed that robots were not replacing humans. When evaluating positions for robots, the PUMA team adopted the policy of never suggesting or providing a robot for a job for which there was a grievance in order not to strain relations with union members.[28] Instead, the PUMA team began by introducing robots in a typical fashion of replacing the dreary, drudgery, and dangerous tasks first; jobs that would not be missed.[29]

It was not just the assembly line worker who had to be convinced of the benefits of automating assembly; the foremen and chief plant engineers also had to be persuaded. The

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[24] Ibid.
[25] Ibid.
[26] Although the strike at GM's Lordstown, OH plant during 1971-1972 was likely in the minds of GM's management, when asked directly about union reaction to the PUMA during the Smithsonian's videohistory recording, the GM employees never mentioned it. Dick Beecher claimed, "the union never, never made a peep … that opposition just simply didn't exist." Frustrated that the press never emphasized the point, Steve Holland added that the United Auto Workers issued a pro-automation statement that the union was "clearly in favor of automation as long as it's applied with respect to the workers and as long as the workers can share in the benefits of that technology advancement." Videohistory transcript.
[27] Jim Schefter, "New Workers on the Assembly Line: Robots that Think," *Popular Science.* June, 1980.
[28] Videohistory transcript.
[29] This obvious approach to implementing automation beginning with the least desirable jobs is now listed in almost all guides to managing automated systems. It is also pervasive in the literature in guidance for selecting possible jobs for robots. In a larger historical context, the rhetoric used in describing jobs as applicable for robots is strikingly similar to the rhetoric Thomas Sugrue quotes concerning automotive jobs deemed applicable for blacks in

flexibility of a human scale robot that could easily be moved from one job to another appealed to foremen. Foremen were accustomed to moving workers among several jobs. However, because the foremen are ultimately responsible for meeting production quotas, they were hesitant to accept that the PUMA would offer a similar flexibility to meet changing demands.[30]

The chief plant engineers were also reluctant to embrace the PUMA. The plant engineers did not enjoy having production ideas coming from outside the plant because they realized upper management would question why the plant engineers themselves had not seen the possible applications for robots. The cost for implementing the robots would also come from the plant's budget, so the engineers did not enthusiastically volunteer to accept the financial burden of training workers to use the robot and maintaining or repairing the robot.[31] Interestingly, the PUMA engineers never make an explicit economic case for their robot.

However, the biggest difficulty implementing the PUMA was due to its very uniqueness: programmability. Before the PUMA robots were "taught" their actions by the process of "lead-through;" that is, manually moving the robot through the required actions. Although the PUMA could be programmed by lead-through, the more powerful design feature was that it could be programmed at a terminal using an interpretive language. Additionally, it was the first robot that could be programmed off-line.[32]

This was a major breakthrough in robot design. The PUMA was the first self-contained, computer-controlled, programmable robot. The computer language control and keyboard programmability came directly out of the academic environment. A rough draft of the original performance requirements for the PUMA from GM did not even mention the idea of a computer

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the 1940s in his book *The Origins of theUrban Crisis*. It could be an interesting study to see how robotics affected diversity in the workplace.
[30] Videohistory transcript.
[31] Ibid.

language for programming. The draft performance requirements only specified record/playback (R/P) control.[33]

In R/P the worker leads the machine through the desired actions while recording the movements. This produces a blueprint of the design that can be repeated as necessary. For Noble, R/P is the road not taken in factory automation, and he only fleetingly acknowledges that it "reigned supreme" in the "special area of robotics."[34] By closing the door to robotics, Noble is ignoring a substantial segment of factory automation as well as an argument against his main thesis that automation took control away from the workers and put it in the hands of the engineers. Noble sees R/P as a method of automation where the skilled craftsman maintained control over machining a part because the machine copied, and could never surpass, the worker's skill. With numerical control, Noble argues, the skill, and the control, rested in the hands of engineers who could program machines from workstations removed from the shop floor. Unfortunately for Noble's thesis, the reason R/P survived in robotics until the 1970s had nothing to do with control of the worker. R/P was used to program robots because the calculations necessary to allow robots to locate an object at any position or orientation are significantly more difficult than for fixed automation, and computers simply could not keep up.

Six degrees of freedom are mathematically necessary for a robot to orient an object at any point in space. They are three translational articulations (right/left, up/down, and forward/back) to determine position and three rotational articulations (pitch, roll, and yaw) to determine orientation. Tracking movement from one space to another involves linear transformations of trigonometric functions. Computer processors were not capable of solving these equations in a

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[32] Ibid.
[33] A rough draft of the "Functional Performance Requirements PUMA System" was sent to Victor Scheinman from Unimation Inc. on December 23, 1976.
[34] Noble, 152.

timely manner until the 1970s. The PUMA was the first robot to include a microprocessor capable of solving the transformations.

Further weakening Noble's argument, Unimation expected the shop floor workers to program the PUMA and even offered training classes. Weiss had to give one of the first in-house training courses. The members of the class were not the engineers from the research labs, but rather the machinists, who he characterized as "people with big thumbs and metal chips under their fingernails and greasy fingernails."[35] These are words from an engineer who definitely has an opinion of class differentiation between engineers and machinists, but not the words of someone trying to control knowledge. Maybe the PUMA engineers were naïve, but they were attempting to give control of programming to the line workers.

The integration of robots on the assembly line was not an attempt to deskill workers, but rather an attempt to modify and, according to the unions, upgrade the skills of the workers. Although Engelberger argued that workers who programmed robots would be able to optimize their use,[36] PUMA programming frequently fell to the engineering staff. Most applications hid the operator (programmable) interface under a simple push-button start/stop user interface. As a result, the boasted flexibility from programmability was never fully realized, but a new intermediary skill level emerged. On shop floors today there exists two levels of computer control within the machine: engineers still write the programs that provide the base functionality, but the machinists write programs using base commands to accomplish their tasks. Engineers provide the tools that machinists use to solve the problem.

Problems with the PUMA, Technology and Image

[35] Videohistory transcript.
[36] David Nobel, *Forces of Production.* p. 188. This remains an ongoing debate.

Vic Scheinman's original robot design was based on the concept that fast computers should lead to fast robots. He quickly learned that the computer was slow relative to the robot. The most complicated feature of automating assembly work is parts recognition. In the 1970s, computer vision technology was just beginning to be incorporated into robotics. Unfortunately, the available microprocessors could not compute the data flow quickly enough to make a viable, vision equipped robot. In the early stages of the PUMA development, GM made the decision to forgo vision recognition in favor of dead reckoning and accurate fixturing. Although the PUMA had acceptable accuracy and repeatability, it became dependent on accurate parts feeding and orientation. Holroyd acknowledged that parts feeding was still a black art and that "the success or failure of a programmable assembly line can sometimes be determined by the availability of dependable parts feeding."[37] Dependence on fixed parts feeding mechanisms severely limited the potential use of the PUMA and almost eliminated the benefits of having a programmable robot. A PUMA equipped assembly line could be reprogrammed in a few minutes, but it would take several hours to retool the dedicated parts feeding and orienting mechanisms.[38]

Unimation continued to experiment with robot adaptability through computer vision with little success. The early experiments with computer vision required strong color contrast between parts and the conveyor belt. A non-GM client that seemed promising was a candy packaging company. The task was simple: pick up dark chocolates off white waxed paper and place them in a box. The job was ideal for a robot because the human workers were frequently bored, suffered from carpal tunnel syndrome, and had a high rate of job turnover. However, the project failed because PUMA's computer recognition software could not compete with the speed

[37] *GM Management Update*, January 1979.
[38] R.C. Beecher, "Programmable Assembly: Is the Technology Base Here?" Presented at the NSF/RANN Production Research and Technology Conference. September 29, 1977.

of the humans. Only recently has computer vision processing been incorporated into practical robotics.

One reason the PUMA failed was that it debuted twenty years before the software and processing power were available to run it. A difficulty in analyzing pre-cursor technologies is judging the level of failure. In a paper presented at an NSF conference in 1977, Beecher recognized the limitations of implementing the PUMA without adaptability features. He also saw the need to introduce robots to all levels of workers at GM's plants to demonstrate that robots are not mysterious, that they are dependable, and that they can be maintained just as any other machine.[39] From Beecher's point of view the PUMA did not fail because it could not be fully implemented, but rather it succeeded in the goal of acquainting people with the *possibilities* of robots.

Lack of computer vision was not the only shortcoming in the PUMA. Another deficiency in the technology was with the programming language that accompanied the PUMA. Versatile Assembler Language, or VAL, lacked some key features, most notably any error checking functionality.[40] Each of the robot's joints ran on a separately programmed servomotor, but the joints did not communicate with each other. When one joint failed, the other joints continued operating without adapting for the loss. Obviously this distorted the arm's position in space and its calibration. More dramatically, if a joint failed, the robot arm could swing and injury its human co-worker. One of the test PUMA's "whacked a couple of guys who got too close;" the technicians called that unit "Killer."[41]

[39] Ibid.
[40] VAL was developed by Stanford graduate student Bruce Shapiro specifically to program the Vicarm/PUMA. It was an iterative language similar to BASIC.
[41] "Robots that Think" p. 57.

In an inter-organizational memo Beecher admitted that the PUMA's "reliability was poor" and traced it to a combination of "workmanship, design, and vendor quality." In response to a GM users group meeting that listed the problems with the PUMA, Unimation sponsored a Hercules study and life test. Hercules was an outside testing firm that analyzed the PUMA's reliaibility. They predicted a mean time between failures (MTBF) of 673 hours for the PUMA system. This surpassed the stated goal of 500 hours MTBF for the PUMA and compared to 400 hours MTBF for the Unimate spot welding robots that were already running in the factory and achieving a 98% up time. For the life tests, both GM and Unimation had a dedicated unit running a durability test. Unimation's test machine ran for 2000 hours with only three failures. The results of these studies resulted in modifications in the PUMA's gear design, controller, and calibration.[42]

Manufacturing Development carefully balanced its enthusiasm for finding new opportunities for incorporating robots without overstating their power. An internal document prepared by Manufacturing Development to familiarize the divisions with possible uses of robots began with optimism that "the capabilities of robots are continually being improved, and no potential application should be abandoned simply because the available robots don't seem to be able to do them," but concludes cautiously, "the purchase of a robot is not the answer to every problem, but represents a new concept as a viable alternative to manual operations and hard automation."[43] Manufacturing Development had the difficult tasks of educating the divisions on

[42] Inter-organizational memo from R.C. Beecher to G.N. Tiberio on the subject of PUMA Reliability, dated November 7, 1980. Letter from Dr. Peter F. Rogers (Unimation) to Mr. Walter Cwycwyshyn on the subject of PUMA Robot Program Status Report, dated January 30, 1981. The three failures during the life test were a DEC board, an old style coupling, and the final motor brush failure.
[43] *Industrial Robot Applications within General Motors*, revised by the Assembly Processing Department, Manufacturing Development. May 12, 1977.

how to incorporate robots appropriately, selecting the best new trends in robotics to explore, and convincing the divisions of new possible applications.

What did the PUMA Achieve?

The PUMA did not revolutionize light assembly. The parts recognition and manual dexterity required of most assembly work have kept robots from replacing humans on the line. However, the PUMA had far reaching effects off the assembly line. The PUMA expanded the growing field of robotics at the university level and still has an active life as a pedagogical tool for demonstrating three-dimensional programming. The PUMA experiment also served as a model for university/industry collaboration.

When Scheinman and Weiss wanted to study robotics at their universities, they had to create their own curricula across multiple disciplines. In comparison, today many universities worldwide now have a PUMA in their engineering labs. It has become a tool for training students and familiarizing them with computer controlled robots. Textbooks that have been through multiple editions still use the PUMA and VAL for teaching the complicated space transformations necessary for robotics programming.[44] By combining mechanical, electrical, and computer engineering principles into a single object, the PUMA is a cornerstone of the three fields.

During development, the PUMA served as a bridge between the university research environment and the industrial workplace. Beecher was introduced to Scheinman while attending an NSF meeting at Stanford. At first he was wary of the graduate student with "a bushy black beard, cutoffs, sandals," who was carrying an anthropomorphic robot in a corrugated

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[44] For example, C. Ray Asfahl, *Robots and Manufacturing Automation*, (John Wiley & Sons, Inc.: New York, 1985, 1992).

carton under his arm. Scheinman earned Beecher's respect quickly by demonstrating a technical innovation that could have direct applications in industry. Steve Holland, currently the Director of Controls, Robotics, and Welding for General Motors, realized the importance of having an application in mind to drive design while he was a co-op student working on computer vision and sensor automation with the PUMA in the GM Research Laboratories. Holland believes that without applications to guide research work, the academic community has difficulty bringing useful products to market. The PUMA demonstrated the powerful effect of interaction and input between industry and university at the early stages of product development and the need to refine an academic project in an industrial environment.

Where did the PUMA Go?

The June 29, 1984 issue of *Robot Insider*, led with the brief boxed text "Bye-Bye Puma." Although the all-electric robots were selling at a brisk pace, Unimation and Westinghouse decided to discontinue marketing the robots under the name PUMA. Connotations of unsatisfactory early versions of the PUMA were one reason the trade name was dropped.[45] When asked where the PUMA went, Floyd Holroyd candidly said, "It went to Japan."[46] Japanese engineers reinterpreted the original concept of a small, electric robot for light assembly work, enhanced it with updated computer software, including vision, and eventually marketed the robot again in the United States. Descendents of the original PUMA are still sold, and GM has over 25,000 servo-electric, computer-controlled robots that are reincarnations of an improved PUMA.[47]

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[45] Westinghouse acquired Unimation in 1983.
[46] Videohistory transcript.
[47] Ibid.

Studying the PUMA and other robotic applications alters the standard account of factory automation by drawing attention away from fixed automation to light assembly. Much assembly work today remains in the hands of humans because robots cannot match the skill of humans. Engineers have not taken control of the shop floor, nor is it clear that it was ever their intent to do so. The failure of GM's Manufacturing Development group to sell the PUMA to management, engineers, foremen, and workers is a reflection on the capabilities and limitations of technology as well as an interesting peek into the engineers' idea of marketing a workplace environment. The fact that the PUMA was incorporated into engineering curriculum and that the PUMA was improved and eventually reintroduced into manufacturing shows that the success of a prototype should not be judged solely on the stated goals of its designers.