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Disruption Lies in the Eyes of the Beholder:
Firm Capabilities and Endogeneity of Technological Disruption

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2007
Industry Studies Association
Working Papers

WP-2007-28
http://isapapers.pitt.edu/

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Draft dated June 26, 2007

Working paper. Please do not cite or quote without author's permission.

I would like to thank Mr. Joseph Engelberger, the father of Industrial Robotics for his valuable inputs to this paper, Mr. Donald Vincent, Vice-President of the Robotics Industries Association (RIA), for making the RIA resources available for my data collection, the participants of the RIA Robotics Forum, Orlando, 2004, and the participants of Atlanta Competitive Advantage Conference, 2006, for their helpful comments and insights.

Disruption lies in the eyes of the beholder: Firm capabilities and endogeneity of technological disruption

Abstract

Failure of leading firms to respond to disruptive technological changes has been explained in terms of their 'choices'. I investigate the disruptive technological changes in the global industrial robotics industry and suggest that 'ability' of the firms play an important role in determining their survival chances. This paper suggests that what may be disruptive (or a sustaining) change may also be a competence-destroying (or a competence-enhancing) change for a firm. Hence, survival during a disruptive change is endogenous to the firm's component and architectural capabilities.

Keywords/phrases: Disruptive technological change; Competence-destroying technological change; Component and architectural capability

One of the most profound effects on the study of technological evolution has been Christensen's (1997) research on technological disruption. By suggesting that technologies that are initially inferior can eventually overturn the mainstream technologies, Christensen's research (e.g., Christensen, 1992; Christensen and Rosenbloom, 1995) has shed new lights on how managers and scholars approach technological evolution and competition. Technological disruption, in its original formulation, was characterized as an industry-wide phenomenon that affects all the firms in an industry and by which new entrants dislodge the established firm. Recent research by Adner (2002), Daneels (2004), Christensen (2006) and others, has helped scholars to respond to the question, '*When are technologies disruptive?*' During disruption, the large manufacturers face the 'innovator's dilemma'- their values and processes lead them to deliberately ignore the disruptive technology (Adner and Zemsky, 2005). Thus large firms often 'choose' not to respond to disruptive threats. Christensen and Overdorf (2000) argued that this strategic *choice* to ignore the emerging technology resulted in the failure of several large firms like DEC and RCA.

The above-mentioned depiction of disruptive technological change (henceforth referred to as 'disruption'- *a technological change to which an incumbent* chooses *not to respond*) raises new, yet unanswered, questions. The broader technology literature provides evidence of exceptions to the phenomenon of failure of large established firms during technological changes (see e.g., Tripsas 1997). Rosenbloom (1988) documented that the National Cash Register survived and eventually regained market success despite the transition from electromechanical to electronic technology. If resource dependence creates an inertia that led to the demise of large firms like DEC (Christensen, 1997), then how does one explain Sony's survival during successive generations of technological changes, including some disruptive ones like the advent of the LCD TV? If disruption indeed has differential effects on different firms, then what might explain heterogeneous firm performance during these changes? These exceptions, especially the fact that several firms have survived numerous waves of technological changes, prompts me to investigate if the notion of disruption is more nuanced than what extant research suggests. In other words, the question '*For whom is a technological change disruptive?*' begs an answer if we are to have a rich theoretical understanding of disruption.

To answer this question, I build up on the broader technology literature and link the survival of firms during disruption to their *abilities*. Leonard-Barton (1992) argues that a firm's capabilities acquired prior to technological changes may create 'competency traps'. Henderson (2006) links competency[1] traps to the phenomenon of technological disruption and observes that the 'dynamics of decision-making in the senior team' as the dominant explanation, for established firms missing out on disruptive innovations, may be 'potentially misleading'. Christensen (2006) also offers tantalizing hints that the *abilities* of firms play a crucial role during disruption when he observes that some disruptive innovations may be 'unattainable to the incumbent leaders, because the technology or capital requirements are simply beyond the reach of the incumbent leaders' (pp.51). Hence, while the role of a firm's *choice* has been adequately addressed in the disruption literature, the potential role of a firm's *ability* to *respond to disruption* has

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[1] Schilling (2005) observes that the terms 'competence' and 'capability' have been used interchangeably in the literature.

largely been overlooked[2]. The motivation for this paper is to extend the notion of disruption by suggesting that the intensity of disruption varies among firms. I investigate the 10 largest global manufacturers of industrial robots and suggest that firm's survival of disruption is endogenous to its *ability*- more specifically to its technological capability. Through the *descriptive-inductive theory building method* (Christensen 2006), I build on Tushman and Anderson (1986) and Henderson and Clark (1990) and suggest that the survival of a firm in the face of disruption depends on the technological capabilities that it possesses.

Next, I discuss the relevant literature. Thereafter, I discuss the industrial robotics industry where a disruption in the mid-1980s had wiped out almost all the U.S. manufacturers of industrial robots. Then, I use the extant literature to explain the observations in the industrial robotics industry. Finally, I discuss the implications and the limitations of this study.

Drivers of disruption: From the industry-level to the firm-level drivers

The notion of disruption has evolved significantly since the early-1990s and has been refined considerably by Christensen (1997, 2006), Adner (2002), Christensen and Overdorf (2000), Danneels (2004), Henderson (2006), Govindrajan and Kopalle (2006) and others. In the early, descriptive stages of this theory, disruption was generally considered an *industry-level phenomenon*. Some of the early papers (e.g., Christensen

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[2] More specifically, the potential role of a firm's *ability* to respond to the technological changes, that share the characteristics identified by Christensen (1997), has largely been overlooked. *These characteristics, discussed on pp.17-19 of this paper, constitute the theoretical boundary of this paper.*

and Rosenbloom, 1995) identified the major constructs of this theory- the performance trajectories of sustaining and disruptive technologies and the performance of the products that customers could absorb. These constructs sought to explain why large incumbent firms in an industry could not survive the challenge from smaller challengers. Christensen (1997) suggests that the products based on the disruptive technologies are typically cheaper, smaller, and simpler than the traditional products. However, over time, the disruptive products are able to meet the requirements of the mainstream customers and causes disruption to the large firms who are embedded to the old technology.

However, exceptions like Intel, HP, Sony, and the Japanese hard-disk drive manufacturers (Chesbrough, 1999), who seem to have survived several challenges of disruption, gave Christensen an opportunity to refine the theory. Consistent with Sull (1999) and Tripsas and Gavetti (2000), Christensen and Overdorf (2000) suggested that survival of firms during disruption is driven by its organizational structure induced inertia. Several large firms, like HP, set-up autonomous business-units that helped the firm survive disruptions. Christensen and Overdorf (2000) and Christensen (2006, pp. 43) points out that the *causes of paralysis of industry leaders lie in the firm-level factors*, e.g., the business models of the firms. This indicates a shift, of the causal mechanism of firm survival during disruption, from the industry level factors to the firm level factors.

Firm-level technological factors as drivers of firm survival during disruption

The possibility of the existence of firm-level causal factors for explaining firm survival during disruption opens an interesting avenue for research. It creates a unique opportunity to investigate if the sources of firm level heterogeneity- for example, the possession of technological capabilities (Tushman and Anderson, 1986; Henderson and

Clark, 1990; Cohen and Levinthal, 1989; Tripsas, 1997) - can explain heterogeneous firm performance during disruption. Henderson (2006) opened the door for such an investigation when she suggested that "...incumbent firms fail to respond to disruptive innovations because responding appropriately requires building competencies they are ill-equipped to acquire and not because they focus too much on existing customers and high-margin opportunities" (pp. 7). The notion that managers focus too much on existing customers was also criticized by Daneels (2004) who argued that the senior managers often do not have the information needed to make appropriate decisions.

Although the role of firm capabilities *during* disruption has not been investigated yet, the role of firm capabilities during technological change has been the focus of intense scrutiny in the technology literature. Utterback and Abernathy (1975) proposed that during its evolution, a technology passes through distinct phases. In the fluid phase, firms experiment with different product features till the emergence of a dominant design. The next phase of evolution- specific phase- emerges with the dominant design. Building on this model, Anderson and Tushman (1990) proposed that firms required different capabilities to compete in the pre- and the post-dominant design phases (or 'eras' according to Anderson and Tushman).

Utterback and Abernathy's (1975) notion of product and process innovation helped researchers categorize innovations into several different types. Two seminal papers in this stream of research are Tushman and Anderson (1986) and Henderson and Clark (1990). Tushman and Anderson (1986) suggested that firms fail to respond to technological changes when they are competence-destroying ones. Gatignon, Tushman, Smith, and Anderson (2002) define competence-destroying innovation as that which 'obsolesces and overturns existing competencies, skills, and know-how'. From this perspective, it is quite possible that the source of large firm paralysis during *what appears to be a disruption is in reality a competence-destroying change*.

Building on Tushman and Anderson (1986), Henderson and Clark (1990) noted that the lack of crucial component and architectural knowledge was detrimental for firm survival in the photolithographic industry. More recently, Klepper and Simmons (2000) observed that prior experience in manufacturing radios helped firms in the television industry. Cohen and Levinthal (1989) referred to the prior knowledge acquired by a firm as its absorptive capacity. Thus, it is quite possible that the source of large firm paralysis during *what appears to be a disruption is in reality a competence-destroying change where the firm lacks the absorptive capacity to respond due to its lack of component and/or architectural capability.* Thus, theoretically, this paper traces its heritage to Utterback and Abernathy (1975) through Tushman and Anderson (1986) and Henderson and Clark (1990). Following Henderson and Clark (1990), I concentrate on component and architectural capabilities as the two drivers of technological competence of a firm. Next, I discuss the pertinent literature that deals with component and architectural capabilities.

Component capability. The engineering design literature has a long history of distinguishing between the components and the product as a whole (see e.g., Marples, 1961). Clark (1985) defined a component as a physically distinct portion of the product that embodies a core design concept and performs a well-defined function. According to Vincenti (1990), component capability includes an understanding of the technologies and materials embodied in components, theories and design heuristics for manipulating them, empirical data on material properties and the performance of alternative design parameters, and the skills and problem solving strategies accumulated in the process of applying this knowledge. Khanna and Iansiti (1997) illustrate the central role of component capabilities in helping mainframe manufacturers develop a number of 'competence-destroying' technological innovations over time. Recently Roy and McEvily (2004) demonstrated that breadth of component capability affected the survival prospects of firms. Following these researchers, I concentrate on component capability as source of persistent performance differential amongst incumbents during disruption.

Architectural capability. Architectural capability of a firm is the knowledge of the linkage among the various components that the firm uses to manufacture its products. Architectural capability affects product performance by determining how, and how well, individual components fit together (i.e. how the set of components works together to deliver the product's functions; cf. Baldwin and Clark, 2000). Henderson and Clark (1990) observed that accumulated architectural knowledge acquired by designing products of the previous generations could blind a firm to the design changes required to respond to new technologies. Other scholars (see e.g., Kogut and Zander, 1992) have used terms such as integrative and combinative capabilities to suggest that architectural capability may assist firms in surviving technological transitions by enabling firms to integrate their component knowledge in new and flexible ways. Thus, I concentrate on architectural capability of incumbents as being a source of differential firm performance during disruption.

Next, I discuss the context of this paper and explain the changes in the industrial robotics industry. Then I explain the changes in terms of the technological capabilities of the firms.

Industrial Robotics industry

Data

I collected data on the industrial robotics industry from various secondary sources, including Industrial Robots- A Survey (1972); Specifications and Applications of Industrial Robots in Japan (1981, 1982, 1984, 1986, 1990, 1992, 1997); Robotics Industry Directory (1982, 1983); British Robot Association's Datafile (1982-83, 1987, 1997); A Survey of Industrial Robots (1980, 1982); Industrial Robot Specifications (Cugy and Page, 1983); Industrieroboter (1979); Handbuch Industrieroboter (1982); International Robotics Industry Directory (1984); International Robotics Products Directory (1989, 1990); Industrial Robots Productivity Equipment Series (1983, 1985). My sample consists of almost 1000 observations of new robot introductions or innovations on existing products by the nine largest global robot manufacturers. In addition to these, various Robotic Industries Association (RIA) publications and trade magazines like Industrial Robot, Industrial Robots International, Robotics Today, Industrial Robots- A summary and forecast (1983), Karlsson (1991), USITC Pub. 1475, Klepper (1985), Sadamoto (1981), and Society of Manufacturing Engineers Industrial Robots Forecast and Trends (1982, 1985) provided valuable information. The product introduction data spanned from 1972 through 1997. I obtained the number of electrical control system patents assigned to each large manufacturer during 1970-1985 from the

USPTO website. I obtained the product-line information for the large manufacturers in 1980 from their annual reports and from various secondary sources and trade journals.

Industrial robotics industry: From inception till the mid-1980s

A generally accepted definition of robot is ‘a reprogrammable multifunctional manipulator designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks’. In Japan, a broader definition classifies certain other forms of transfer devices as robots too. The word robot is derived from a Czech word ‘robota’ which means drudgery. The industrial robot industry started in the U.S. with a group of companies whose expertise lay in mechanically engineered products- machine tools, material-handling, and related machinery. The pioneers of the industry include American firms like Unimation (a subsidiary of Condec Corp.), Cincinnati Milacron, Prab, and AMF Versatran. Unimation sold the first industrial robot to General Motors in 1961. By 1969, there were about 20 robots in service in the U.S., and in 1970 the U.S. robot population increased to 200. This number increased to 3849 by 1980. By the early 1980s, large U.S. manufacturers like General Electric, Westinghouse, and IBM had started manufacturing robots. In 1982, there were about 50 U.S. manufacturers of robots. Two of the largest firms (Unimation and Cincinnati Milacron) accounted for almost 60% of the total shipments in the U.S. In 1984, General Motors, the largest buyer of robots in the U.S., entered into a technical collaboration with Fanuc of Japan to manufacture robots. General Motors-Fanuc (GMF) sold robots that were largely designed by Fanuc in Japan. Most of the U.S. manufacturers, including GMF, however, exited the industry by the end of the 1980s. Figure 1 shows the robot population of various countries during the time of this study.

Japan has been the leader in the demand for industrial robots and USA has been the traditional second-largest market for robot manufacturers. This is consistent with Mansfield's (1989) observation that Japanese users used larger number of robots as compared to the American users. Figure 2 shows the severe contraction of net new orders of industrial robots in the U.S. during the mid 1980s and early 1990s. The number of American robot manufacturers, which had increased from about 7 in the early-1970s to about 50 in the early-1980s, decreased to just 1 by the mid-1990s.

Insert Figure 1 and Figure 2 about here

The evolution of the industrial robotics industry is, however, largely synonymous with the evolution of the industry in Japan. In 1967, the first robot was imported into Japan. In 1968, Kawasaki Heavy Industries started manufacturing robots in technical collaboration with Unimation. Subsequently other electrical and electronic firms like Hitachi, Toshiba, Fuji Electric, and Fanuc started manufacturing robots. Shortage of labor and the oil shocks of the 1970s provided the boost to the industrial robotics industry in Japan. By the end of 1970s, Japan's robot population was around 14000 and there were about 140 Japanese robot manufacturers. The early entrants in the European robot industry were firms like ABB, Olivetti, and Siemens, and large automobile manufacturers like Volkswagen, Fiat, Renault, and Volvo.

The primary use of robots includes casting, forging, spot welding, painting, machining, assembly, palletizing, inspection and testing, and education. Traditionally, in the U.S. and in Western Europe, welding robots are about 30% of total population of robots followed by casting robots. In contrast, the predominant traditional use (approx. 30-40%) of robots in Japan has been in the assembly jobs. In the U.S. and Europe, the automobile industry was the largest buyer of robots, but in Japan, electrical and electronic product manufacturers were the largest buyers.

Description of a robot

A robot hand (or the manipulator) is actuated by the command from the controller, which can be a computer or a teach pendant. The command goes through a power conversion unit, which translates the electric signal to drive the actuator. Robot's movements are powered by one of the three types of actuators- electrical, hydraulic, or pneumatic. In an electrical actuator, the power conversion unit consists of a digital-to-analog converter and an amplifier with a power supply source. In a hydraulic actuator, the power conversion unit consists of a pump and a cooler. In a pneumatic actuator, the power conversion unit typically consists of compressor, servo-valve, and an amplifier.

Two of the most important performance attributes of a robot are the repeatability (i.e., the precision with which a robot can return to the same position) and the load capacity (i.e., the maximum load that the robot's arm can carry) (Klepper, 1985; Katila and Ahuja, 2002). Everything else being equal, the lower the value of a robot's repeatability, the better it is, and higher the value of load capacity, the better it is. Traditional manufacturers of robots like Unimation and Prab have relied on hydraulic actuators to control their robots. Robots with hydraulic actuators had the highest payload capacity. Robots with electric actuators had better repeatability and accuracy. The main advantage of robots with pneumatic actuators was low cost.

Disruption in the industrial robotics industry

Although early robot manufacturers utilized hydraulic actuators, changes in both the demand conditions and technological innovations in electrical control technology ensured that most of the robots manufactured since the mid-1980s utilized electrical actuators.

Changes in the demand conditions: Although the early users of robots were the automobile manufacturers, it was clear by the end of the 1970s that the future of robotics industry lay in small-parts assembly. The Carnegie-Mellon University Robotics Survey (1981) suggested that since 1976, an increasing portion of the users of industrial robots were the ones engaged in small-batch sized custom manufacturing rather than those engaged in mass production techniques. By 1987, over 60% of the total population of industrial robots was used in spot welding of car bodies in the automotive industry and most of the automobile manufacturers had no further scope for automation in the production processes (Industrial Robot, Sept. 1987, pp. 150).

The growth of the small-batch manufacturers coincided with the advent of small-parts assembly techniques used in manufacturing computers, calculators, cell phones, and other electronic gadgets. Whereas the robots for traditional assembly were developed with payload capacity as the primary performance criterion, the robots for small-parts assembly were developed for high-technology and mission-critical assembly operations. In the small-parts assembly robots, accurate handling of delicate parts with high repeatability became the primary product attribute (Intelledex Inc. Report published in Robotics World, June 1983). Electrical robots were better suited than either hydraulic or pneumatic robots for the operations requiring high repeatability. During the 1980s, more and more electronic assembly plants started relying on the light assembly electric robots not only for higher repeatability as compared to human labor, but also for the cleaner operations that reduced the chances of contamination of the wafer surface from the spillage of fluids in the hydraulic robots. Demand from the electronic sector fueled a significant portion of the growth of the industrial robotics industry during the 1980s and 1990s (Carlisle, 2003). Alongwith the electronic assembly plants, small appliances, food processing, and pharmaceuticals industries also valued the high repeatability and other performance features of the electrical robots. Figure 3.1 shows the relative growth in the demand of electrical small-parts assembly robots as compared to the growth in sales of hydraulic arc-welding robots in the U.S. in mid-1980s. Figure 3.2 shows the proportion of electrical robots sold to the electrical and electronic assembly industry as percentage of the total robots shipped in Japan from 1979 to 1989. Figure 4.1 shows the dramatic changes in the proportions of assembly, welding and machine loading/ unloading (i.e., machine tending) robots in the robot populations of Japan and the U.S. in the early 1980s. Figure 4.2 shows the proportions of assembly, welding, and machine tending robots in the domestic shipments of robots in the U.S. during late-1970s and early 1980s.

Thus, the altered demand condition, especially from the 1980s onwards, was one of the factors that led to the predominant use of electrical robots over the hydraulic and pneumatic ones.

Insert Figures 3.1, 3.2, 4.1 and 4.2 about here

Innovations in the microprocessor and electrical motor technologies: The small-parts assembly tasks typically require controlling the movement of a robot-arm in six or more axes. Movement control, in turn, requires real time processing of complex algorithms using microprocessors. Innovations in the computing power of microprocessors in the late-1970s opened new fields of applications of industrial robots. Manufacturers were now able to design robots capable of performing small-parts assembly tasks (Robotics World, June 1983, pp. 17).

In addition to the innovations in microprocessors, these new applications of robots also benefited from the innovations in the electrical motor technologies during the 1970s and 1980s. Since the early-1970s, significant innovations enhanced the capabilities of brushless AC motors (Brown, 1983). Simultaneously, increases in the AC servomotors power output in the early 1980s enabled the electrical robots to increase the load capacity. Asea's (now ABB) introduction of new robots exemplifies the innovations in the electrical technology. ABB introduced the first robot with electrical actuator in 1974. As with any new product that leads to disruption, this new robot, IRB-6, had a load capacity of 13.2 lbs. This was considerably inferior to the rated load capacity of 99 lbs of MKII Series 4000 hydraulic robots by Unimation available since 1972. Also in 1972, Prab’s Third Generation hydraulic robots had achieved a load capacity of 55 lbs. By the end of the 1970s, ABB's electric robots had surpassed these load capacities. Spray painting robots also exemplify the improvements in the electric robot technology. Spray painting had traditionally been the stronghold of hydraulic robots, but innovations in the electric motor technology enabled ABB to manufacture electric spray painting robots in 1988.

Changes in the components used in manufacturing automobiles and other products also helped electrical robots to replace the hydraulic robots in the traditional assembly and manufacturing firms. The average weight of the parts handled in the automotive industry were around 25 lbs in 1980 and this figure was coming down as more and more parts were being manufactured with light-weight metals like aluminum rather than steel. The Industrial Robots- A Delphi Forecast of Markets and Technology (published by the Society of Manufacturing Engineers, 1982, 1985) predicted that the average weight of parts in the automobile industry to come down to around 15 lbs by 1985. As the weight of the components reduced, the users of robots demanded medium load capacities rather than high load capacity robots. This implies that, over time, more and more buyers could rely on the electric robots for their load capacity requirements.

Yet another significant technological innovation that greatly enhanced the suitability of electric motors for small-parts assembly jobs is the development of the Direct-Drive robots. Originally developed by the Robotics Institute of the Carnegie-Mellon University in 1980, these robots eliminated the use of gear-reducers in the robots. As a result of this change, the repeatability of the robots could be enhanced significantly. Adept Technology Inc. introduced the first direct-drive robot in 1983 and attained a repeatability of 0.001 inch. This was an order-of-magnitude better than the repeatability of traditional robots with gear reducers.

The above-mentioned innovations helped the electrical robots to be applied not only to the emerging small-parts assembly applications involving high repeatability and low load capacities, but also to the mainstream traditional hydraulic robot applications involving higher load capacities[3]. Since industrial robots have distinct components and

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[3] Although initial research by Christensen suggested the importance of *vertical differentiation*, latter extensions by Christensen and others suggested that *horizontally differentiated* products could also lead to disruption. Ecton Inc.'s Doppler Echo Machine (Harvard Business School Case # 5-600-129) and Du Pont's Kevlar fiber (Harvard

subsystems that are linked into product architectures, and since the industrial robotics industry has faced serious upheavals during the late-1970s and early 1980s, this industry is well suited for an investigation of the role of firm capabilities during disruption. Next, I map the technological changes in this industry to Christensen's notion of disruption.

Mapping the changes in the industrial robotics industry to disruption

Christensen's (1997) notion of disruption can nicely explain these changes in the industrial robotics industry. The traditional hydraulic robots emphasized load capacity as the primary performance criteria. Arm oscillation in the hydraulic robots severely restricted the repeatability that could be achieved with these robots. The electrical robot manufacturers initially targeted a different market segment, where the buyers emphasized repeatability of the robot as the primary performance criteria. Similar to the disruption of minicomputer manufacturing by the personal computer manufacturing (Christensen and Overdorf, 2000), the hydraulic robots were disrupted by the electrical robots. As shown in Figures 5 and 6[4], the traditional hydraulic robots were high on the load capacity dimension, but low on the repeatability dimension. The traditional electrical robots were high on the repeatability dimension and low on the load-capacity dimension. However, the technological changes in electrical technology during the late 1970s and early 1980s

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Business School Case # 9-698-079) were both sources of disruption and were horizontally differentiated from the mainstream products in their respective markets.

[4] Figure 5 is derived from Figure 11 (described later) by taking the best repeatability figures for the electric and hydraulic robots separately. Similarly, Figure 6 is derived from Figure 10 (also described later) by taking the highest load capacity of the electric and the hydraulic robots.

moved the electrical robots to even better repeatability and higher load capacities. Performance improvements in the hydraulic robots were comparatively incremental. Figures 7 and 8[5] show the performance improvements in both hydraulic and electrical robot markets. These figures have the three basic elements for disruption as described by Christensen (1997). These are- the upward sloping trajectories of performance improvement for the hydraulic and the electrical robots, and the performance (i.e., load capacity) demanded by industrial robot users.

The challenge to the industrial robot manufacturers in the late-1970s and early-1980s satisfies most of the characteristics of disruption (Govindarajan and Kopalle, 2006). The characteristics are:

a) Electrical robots in the 1970s and early 1980s under-performed the hydraulic robots in the performance attribute (i.e., load-capacity) that the mainstream customers (i.e., the automobile manufacturers) valued.

b) New features (e.g., repeatability) offered by the electrical robots were not highly valued by the mainstream users.

c) Disruptive products are typically cheaper than the mainstream products. Likewise, the electric robots were also typically cheaper than the hydraulic robots. Figure 4 shows that between 1980 and 1983, the U.S. population of assembly robots, which are electric robots, increased dramatically. Figure 9 suggests that, for the first time in the history of the industrial robotics industry, the average price of robots in the U.S. fell during this period. In the early 1980s, the electrical robots for

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[5] Similar to Figure 6, this figure is also derived from Figure 10

small-parts assembly would typically cost around $20,000 and the hydraulic robots for traditional jobs would cost around $60,000.

d) Over time, the performance of the disruptive products improves and satisfies the demand of the mainstream customers. As shown in Figures 7 and 8, by the early-1980s, innovations in the electrical motor technology helped electrical robot manufacturers like ABB and Fanuc to meet the needs of the most demanding welding and painting jobs in the automobile factories.

The preceding discussion makes it clear that the industrial robotics industry faced disruption during the late 1970s and early 1980s.

Insert Figures 5-9 about here

Consequences of disruption in the industrial robotics industry

The effects of this disruption were felt across three continents. In the U.S., most of the four original pioneers of industrial robots did not survive the 1980s. Unimation was taken over by Westinghouse in 1984, which in turn, sold the direct-drive robot unit as Adept Technologies in 1984, licensed the hydraulic robot business to Prab in 1987 and sold the rest of the electric robot business to a Swiss robot distributor, Staubli, in 1988. In 1990, Cincinnati Milacron sold its robot business to ABB. AMF Versatran was taken over by Prab in 1979, which, in turn, disbanded its robotics business around 1989. In Europe, ABB acquired the Norwegian company Trallfa, the pioneer of the continuous-path hydraulic painting robots, in 1985. In Japan, Kawasaki terminated its contract with Unimation in 1985 and entered into a new contract with Adept to manufacture direct-drive electrical robots. Despite these drastic consequences, several manufacturers like

ABB, Hitachi, Kawasaki, and Matsushita survived the disruption. Of these survivors, Mitsubishi and Kawasaki successfully switched from being hydraulic robot manufacturers to electrical robot manufacturers.

Next, I concentrate on the abilities of the large robot manufacturers to explain their heterogeneous performance during disruption.

Investigation of the drivers of heterogeneous firm performance during disruption in the Industrial Robotics industry

To explain the differential effect of disruption in the industrial robotics industry, I concentrate on the largest robot manufacturers in the U.S., Europe, and Japan like Unimation, Prab, Cincinnati Milacron, Asea (now ABB), Kawasaki, Fuji Electric, Fanuc, Hitachi, Mitsubishi, and Matsushita. This is consistent with most of the extant research on disruption (e.g., Christensen, 1997), which concentrate on the large manufacturers only. During the late 1970s, the combined market-share of these manufacturers was more than 50% in their respective home markets. In the U.S. in 1980, Cincinnati Milacron, Unimation, and Prab controlled almost 70% of the total marketshare. Figure 10 shows the corporate sales and robot sales of these manufacturers in the early 1980s.

Since the hydraulic robot technology was supplanted by the electrical robot technology, I first investigate if the electrical robots produced by these manufacturers indeed had better repeatability and if the electrical robots eventually matched the load capacity of the hydraulic robots. Thereafter, I look into the capabilities of the manufacturers as drivers of differential firm performance during disruption.

Comparison of the performance parameters of hydraulic and electrical robots: I compared the load capacity (in pounds) and repeatability (in inches) of the robots introduced by the major robot manufacturers mentioned above. Figure 11 shows the maximum Load Capacity of the products introduced by the various industrial robot manufacturers over the years. The trajectories of the improvements of load capacity in the industrial robots industry closely parallels those of the hard disk drive capacities mentioned in Christensen and Rosenbloom (1995, Fig. 4, pp.244). Hydraulic robots by Prab have been the historical leaders in the load capacity, followed by the hydraulic robots of Unimation. The four leaders in load capacity during the 1970s were Prab, Unimation, Cincinnati Milacron, and Kawasaki- all manufacturers of hydraulic robots at that time. However, by the early 1980s, electrical robot manufacturers were catching up with the load capacities of all these manufacturers (except the extremely high load capacity robots by Prab). ABB’s electrical robots had almost achieved the load capacity of Cincinnati Milacron’s hydraulic robots around this time. By the mid-1980s, several electrical robot manufacturers including ABB, Fanuc, and others had surpassed the highest load capacity of Unimation robots. By the early 1990s, ABB’s electrical robots were challenging the highest load capacities of the Prab robots.

Figure 12 provides the information on the improvements of robot’s repeatability. Since the mid-1980s, Japanese firms have been the leaders in repeatability. Fuji achieved a repeatability of 0.0004 inch in 1986, and Matsushita was the closest to this with a repeatability of 0.0006 inch achieved in 1997. Unimation, a traditional manufacturer of hydraulic robots, tried to face the challenge from the electric robot manufacturers by taking over Vicarm and introducing electrical robots in the early 1980s. Unimation’s repeatability in the electrical robots approached that of Matsushita in the mid-1980s. However, Cincinnati Milacron’s electric robots’ repeatability lagged that of the major competitors. Kawasaki's efforts to introduce highly repeatable electric robots were largely successful and, by the mid-1980s, its robots achieved better repeatability than those of the ABB robots.

Insert Figures 10, 11, and 12 about here

Thus, the load capacity of the hydraulic robots of the largest manufacturers was initially better than the load capacity of the electrical robots. Similarly, repeatability of the electrical robots by the largest manufacturers was also better than the repeatability of the hydraulic robots. Hence, the product performance data from the robotics industry are indeed consistent with disruption. Next, I investigate the technological capabilities of the large manufacturers.

Technological capabilities and the differential effects of disruption

Component capability of large manufacturers: As a result of the surge in demand for the small-parts assembly robots, the knowledge of components used in electric robots, like the converters and amplifiers, became crucial. Firms, that entered the robotics industry from electrical engineering driven industries like the numerical control systems manufacturing, are likely to find this transition quite easy. Given their pre-existing absorptive capacity in electrical engineering driven products, the challenge to manufacture converters and amplifiers for robots will be a competence-enhancing one. Kumaresan and Miyazaki (1999) observed that the electrical control systems became an important part of industrial robots and the Japanese manufactures historically had a lead over the American manufacturers in this technology. On the other hand, firms that entered the industrial robotics industry from primarily mechanical engineering driven industries like machine tools, are going to find this transition a competence-destroying one. This is because the crucial aspects of a mechanically engineered system are the mechanics and the movement of the components and subsystems used in the product. In case of a robot, the crucial aspect of the hydraulic robot is the pump and the distribution of the fluid through the use of valves.

Hence, in the case of disruption in the industrial robot industry, the firms that had prior experience in electrical engineering products were likely to be in a competence-enhancing scenario and the firms that had prior experience in the mechanical engineering fields were likely to be in a competence-destroying scenario.

To track the component capability of the large manufacturers, I explored the number of electrical control system patents that each of the large manufacturers held in the U.S. during the period 1970-1985. Cohen and Levin (1990) suggested that patents held by a firm represent its knowledge. Katila and Ahuja's (2002) study on the industrial robotics industry points out that the more knowledgeable firms are able to search deeper and introduce more products. Accordingly, I assume that if a firm was assigned a patent in electrical control systems, then it possessed the component knowledge required to manufacture robots with electrical actuators. Figure 13 shows that the Japanese manufacturers like Hitachi and Matsushita held more than 400 electrical control systems related patents during 1970-1985, but Unimation and Prab held less than 10 patents during that period. Thus, Unimation and Prab had limited component capability as compared to other manufacturers.

Hence, from the component capability standpoint, disruption in the industrial robotics industry was relatively more competence-destroying for the non-survivors like

Unimation and Prab and relatively more competence-enhancing for the survivors like ABB and Hitachi.

Architectural capability of large manufacturers: The increasingly sophisticated demand from the electronics industry during the 1980s meant that the manufactures of robots had to precisely design, link the components, and manufacture the robots so as to reduce the downtime required for maintenance. Among other things, this implies that the firms had to link the components and subsystems in ways to reduce the friction among the components, effectively dissipate the heat generated by the operation of the system, and so on. From an engineering viewpoint, firms acquire architectural capability by manufacturing different products in which the components and subsystems are linked in different ways. Knowledge of linkage among the components and subsystems helps firms to create new products and also creates the absorptive capacity to realize the linkages among the components in robots with different actuators. Hence the product-line breadth (Kekre and Srinivasan, 1990) of firms should indicate the architectural capability of firms. The more the product line breadth of a firm, the more likely it is that the firm can utilize some of its existing knowledge of architectural capability in manufacturing robots. Hence, I explored the product-line breadth of the robot manufacturers as a measure of architectural capability overlap of the manufacturers. From the annual reports and various other secondary sources, I measured the number of different products that a manufacturer offered in 1980. For example, Unimation manufactured only robots in 1980, and hence its product-line breadth is ‘1’. Hitachi, manufactured several different types of products, like household equipments, robots, machine tools, and so on, and its product-line breadth was ‘15’. Figure 14 documents the product-line breadth of various manufacturers. It is evident that Hitachi, Matsushita, Mitsubishi, and some other manufacturers had a higher value of product line breadth than either Unimation or Prab.

Hence, from architectural capability standpoint, disruption in the industrial robotics industry was likely to be more competence-destroying for the non-survivors like Unimation and Prab and likely more competence-enhancing for the survivors like Matsushita and Mitsubishi.

Insert Figures 13 and 14 about here

Technological capability and the fate of the firms: Figures 13 and 14 suggest that for the non-surviving U.S. manufacturers like Unimation, and Prab, unfortunately, disruption was a relatively more competence-destroying one than for the survivors like ABB, Hitachi, and others. Unimation was essentially a de-novo entrant in the industrial robotics industry. It had less than 10 electrical control system patents. It tried to meet the challenge by introducing electrical robots in 1980s, but as Christensen (1997) suggests, large producers usually wait too long before they adopt the new technology. Prab had about 6 electrical control system patents and concentrated on manufacturing hydraulic robots. In terms of component capability, Cincinnati Milacron with almost 100 patents was better placed than both Unimation and Prab to meet the challenge of manufacturing robots with better repeatability, but was worse off to meet the challenge as compared to Hitachi, Fuji Electric, Matsushita, and Mitsubishi Heavy Industries. Hitachi held more than 1000 control system patents during 1970-1985. Matsushita held more than 400 control system patents during that period. Thus, from the component capability perspective, the challenge in the industrial robotics industry was largely a competence-destroying one for the non-survivors- Unimation and Prab. For the survivors- Hitachi and others- the challenge was a competence-enhancing one.

In terms of architectural capability too, Unimation and Prab were distinctly disadvantaged against their competitors like Hitachi, Fuji, Matsushita, and Mitsubishi Heavy Industries. Unimation, being a de-novo entrant to the industrial robotics industry manufactured only robots. Prab, a conveyor belt manufacturer, diversified into robots. Unlike Unimation and Prab, Kawasaki had other businesses, like the machine tool and the plastic molding machine manufacturing businesses, which provided some architectural knowledge to manufacture the new type of robots. For firms like Hitachi, Fanuc and others, who possessed the absorptive capacity to develop the electrical engineering components for electrical actuators and the necessary linkages, disruption in the industrial robotics industry was largely a competence-enhancing one.

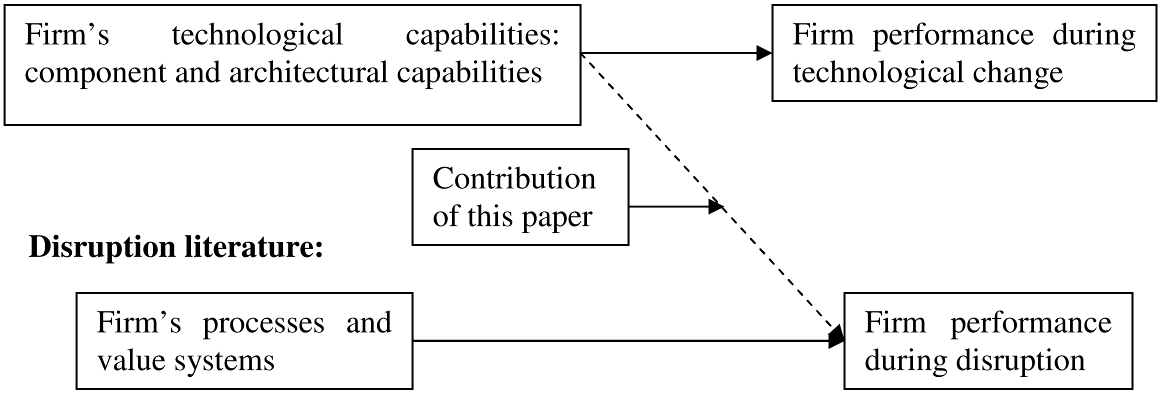
Contrary to Christensen's (1997) notion of the dependence of large firms on existing customers, there are numerous evidences to suggest that it was *unlikely that the large robot manufacturers had ignored the emergence of the electrical robot as a strategic choice*. Industrial Robots International (4/11/1983, pp.2) reported that Japanese automakers were shifting from the hydraulic to the electrical robots due to the improved power output of electrical actuators. The prospect of a possible shrinkage of the traditional hydraulic robot market in the automobile industry had prompted Unimation, the largest U.S. robot manufacturer in the 1970s, to acquire Vicarm Inc. in 1977 for manufacturing electrical robots. In the early 1980s, Unimation introduced the PUMA range of electric robots, which were capable of a repeatability of 0.0008 inch. Cincinnati Milacron, which manufactured only hydraulic robots in the 1970s, started manufacturing electric robots in 1982. Kawasaki, traditionally a manufacturer of only hydraulic robots, terminated the collaboration with Unimation in 1985, and entered into a new one with Adept Technology, the pioneer of direct-drive electrical robots. By the early 1990s, Kawasaki's entire portfolio of industrial robots comprised of only electrical robots. Industrial Robots International (4/11/1983, pp.2) reported that all major hydraulic robot manufacturers of Japan were introducing electrical robots in the early 1980s. By 1983, 56% of the industrial robots installed in the U.S. had electrical actuators and the trend was towards greater use of electrical robots (Industrial Robots, 1983). Moreover, as shown in Figure 3, by the early 1980s, the assembly robot segment was already the largest robot segment in Japan and, in both Japan and the U.S., it was growing faster than the mainstream welding robot segment. Additionally, Robot News International, a magazine popular among the manufacturers and the users, predicted in its June 1982 issue that between 1981 and 1991, the Assembly robots would grow 3% to 23% of the total robot population in the U.S.

Thus, as suggested by Henderson (2006), the survival of firms during disruption is likely driven by their *abilities*- the component and architectural capabilities.

Discussion

This paper sought to answer the question, '*For whom is a technological change disruptive?*'. In the context of the industrial robotics industry, *the answer is that the change is a disruptive one for a firm that faces a competence-destroying change.* Theoretically, this paper brings together the two distinct streams of technological capability literature and disruption literature. While the traditional technological capability literature has pointed out the beneficial role of firm-level capabilities during technological changes (Henderson and Clark, 1990), the disruption literature has suggested that firm's processes and value systems play a crucial role during disruption (Christensen and Overdorf, 2000). This paper brings these two streams of literature together and suggests that the findings of prior research on competence-destroying technological changes can also explain firm performance during disruption. The theoretical contribution of this paper is shown below:

Technological capability literature:



Christensen's (1997) notion of disruption has occupied the center-stage of the technological change literature for more than a decade. The failure of firms to respond to disruption has been explained in terms of their *choices*- the new emerging market appears financially unattractive to the large firms and hence the value systems of large firms act as a source of inertia that prevents the large firm from responding effectively to the disruptive challenge from new entrants. Although the 'choice' argument of disruption is well documented, my research suggests that the effects of disruption on the firms are more nuanced than originally thought. Consistent with Henderson's (2006) assertions, I find that the causal mechanism of firm survival during disruption may also lie in the competencies acquired by the firm prior to the change. Consistent with the suggestions of

Tushman and Anderson (1986), it appears that what may be a severely disruptive competence-destroying technological change for one firm may be a sustaining competence-enhancing change for another. Whether a challenge is disruptive or sustaining depends on the technological capabilities possessed by the firm, i.e., disruption lies in the eyes of the beholder. My findings, to some extent, diverge from those of Henderson and Clark (1990). Henderson and Clark (1990) found that even if the firms possessed the component capability, their architectural capability made them inertial. In the case of the robotics industry I do not find any evidence of that inertia. Large robot manufacturers seem to have benefited from both the component and the architectural capabilities.

The paper opens up new avenues for research, especially by suggesting that the firm's 'ability' to respond to disruption has largely been overlooked. Building up on Henderson (2006), this paper also suggests that the primary driver of firm paralysis during disruption is the capabilities possessed by the firm. Firms' absorptive capacity can ensure that what is a disruption for one firm is a sustaining change for another firm. This paper supports Hannan and Freeman's (1977) perspective that coarse-grained changes (like the one in the industrial robotics industry) should favor the large generalist firms over the small specialist firms. The findings of this paper are also consistent with Markides and Williamson's (1996) perspective that related diversification may be beneficial for the firms.

This paper's findings are consistent with those of several other researchers who have investigated the industrial robotics industry. Dahlin (1993) predicted that the Japanese manufacturers would continue to dominate the robotics industry and this paper explains why some of them have been successful against the American manufacturers. This paper also extends Katila's extensive investigation of the industrial robotics industry in two ways. First, Katila (2004) suggested that firms with technological experience are likely to be more innovative and this paper points out that experience with the electrical engineering technology was more important than mechanical engineering knowledge. Second, Katila (1999) examined the robotics industry from early the 1980s onwards and I investigate the industry from 1972 onwards, thereby extending Katila's observations to a longer time period.

The paper suffers from several drawbacks. First, it lacks the panel data analyses that could have helped establish a stricter causality. Second, I do not investigate the history and capability of several other large robot manufacturers like Kuka Robotics of Germany. Third, in addition to technological capabilities, a firm possesses several other types of capabilities and routines, like the complementary capabilities and marketing capabilities, and I do not take those into account. For example, Benner and Tushman (2003) suggest that a firm's process management practices affect its capabilities. In this paper I do not investigate the process management practices of a firm. Firms frequently exploit their complementary assets (Rothaermel, 2001) and I do not take these assets into account in my paper.

Despite these limitations, this paper brings prior research on technological capabilities into the realm of disruption. It suggests that even if a firm is able to overcome its organizational structure induced inertia by creating separate strategic business units for the disruptive products (Christensen and Overdorf, 2000), it may lack the vital component and architectural capabilities to respond effectively and may be forced to exit.

Figure 1: Robot population (Source: Robotic Industries Association (RIA) publications)

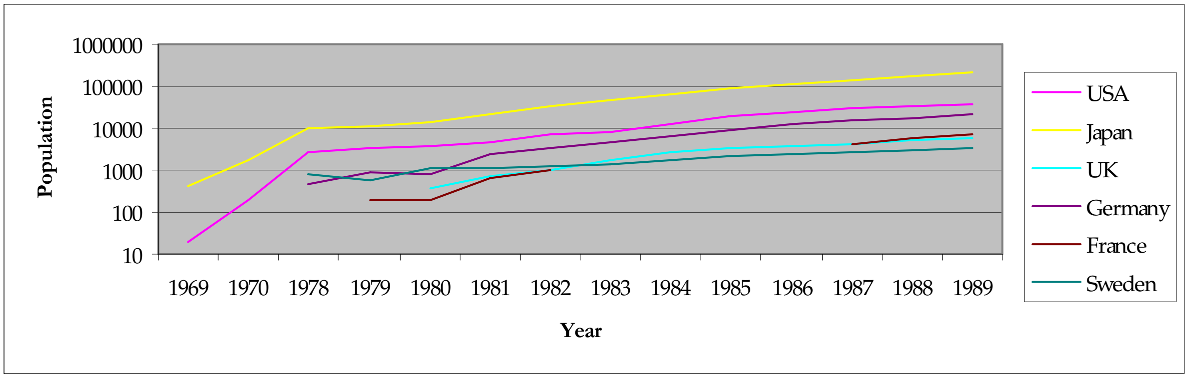


Figure 2: Net New Orders (in $ MM) of Industrial Robots in the U.S. (Sources: Industry Flash, Vol.1, No.4; Industrial Robot International- various years)

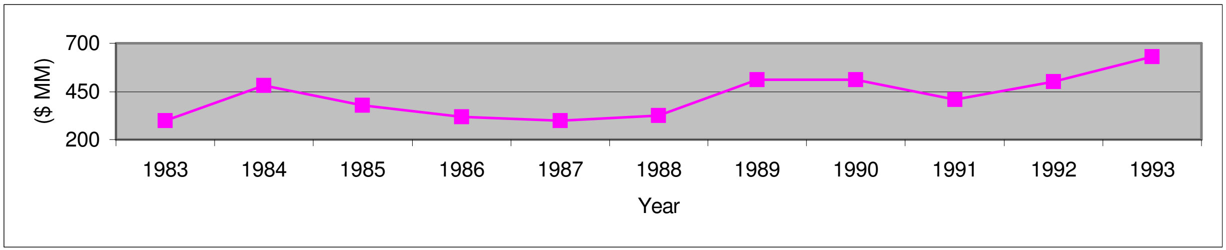


Figure 3.1 Evidence of the growing importance of electrical robots- Sales in $MM of hydraulic arc-welding robots and electrical small-parts assembly robots in the U.S. (Source: Industrial Robot, March 1986, pp.6)

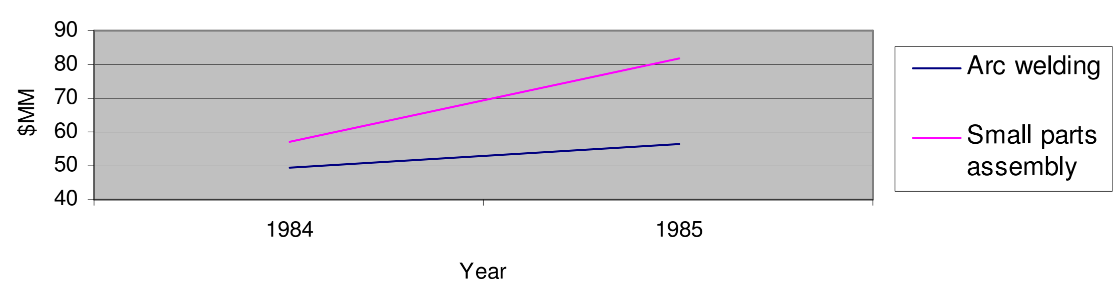


Figure: 3.2 Evidence of the growing importance of electrical robots- proportion of electrical robots sold to the electrical and electronic assembly industry as percentage of the total robots shipped in Japan (Sources: Sadamoto, 1981, pp. 134; Karlsson, 1991)

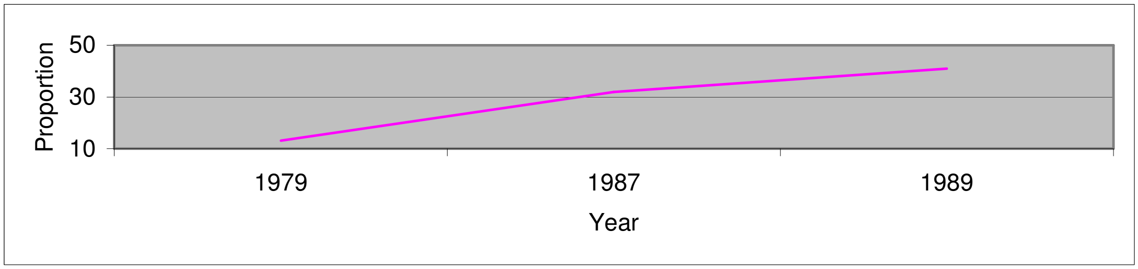


Figure 4.1: Proportion of robots of various applications in the total robot populations of U.S. and Japan (Machine tending= Machine tool loading and unloading robots) (Sources: RIA Worldwide Survey- 1981, 1986; Industrial Robot- 1987-1994)

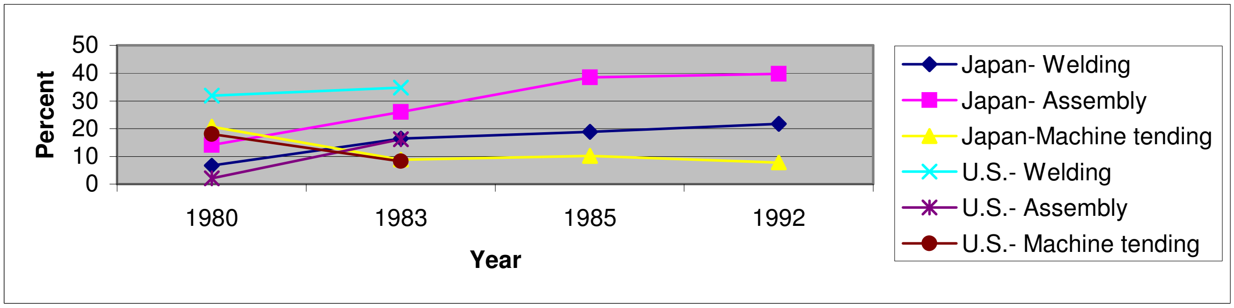


Figure 4.2: Proportions of robots of various applications in the domestic shipments of robots in the U.S. (Machine tending= Machine tool loading and unloading robots) (Source: USITC Pub. 1475, Dec. 1983)

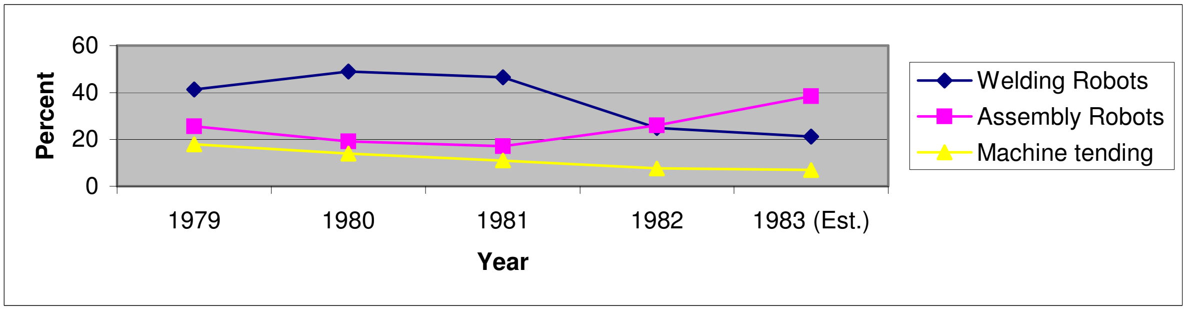


Figure 5: Improvement of repeatability of hydraulic and electric robots (Sources: Database created from several secondary sources)

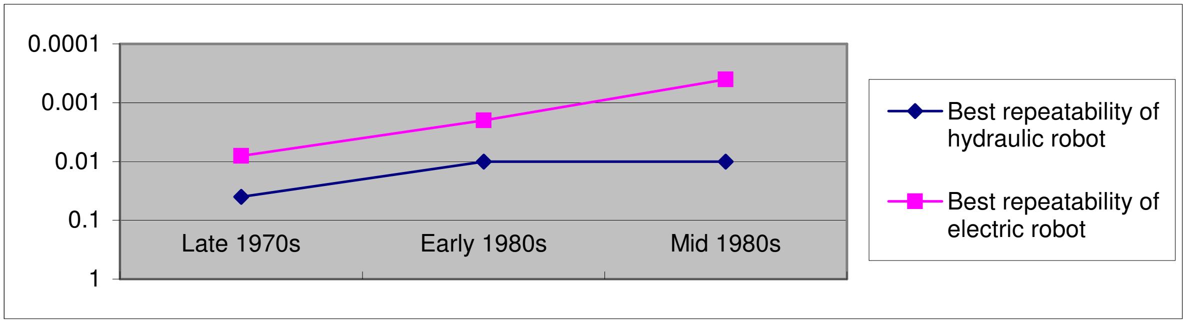


Figure 6: Improvement of maximum load capacity of hydraulic and electric robots (Sources: Database created from several secondary sources)

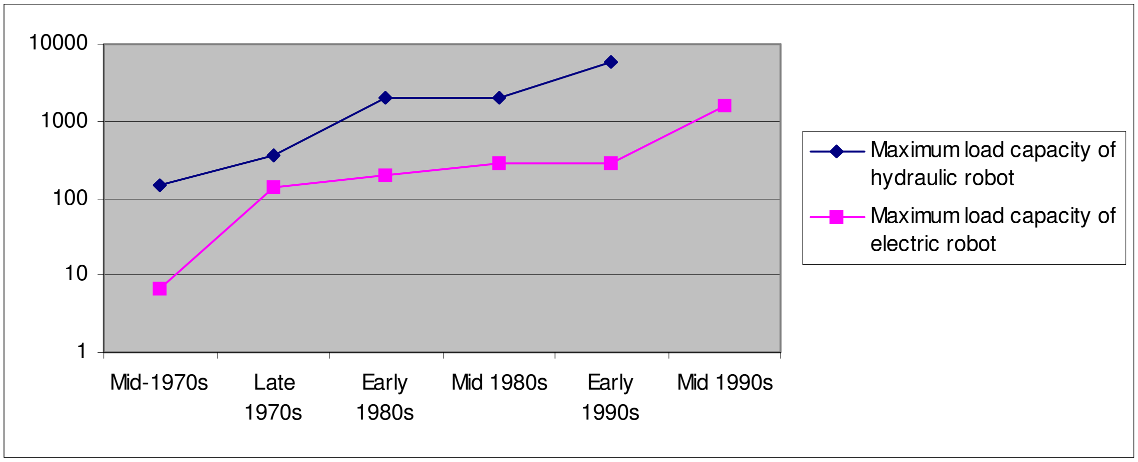


Figure 7: Three basic elements for disruption in the industrial robot industry

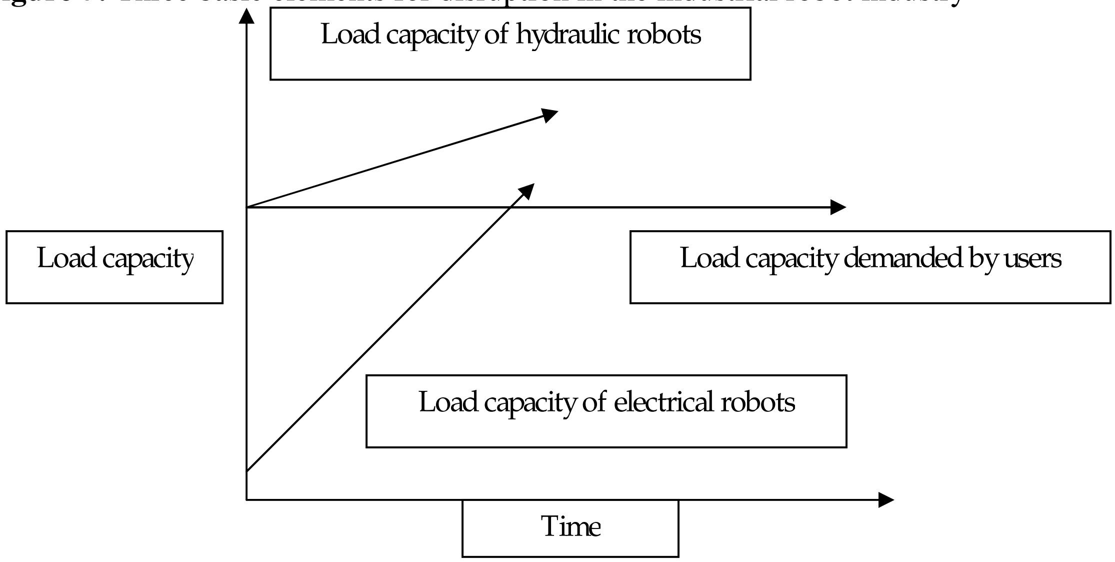


Figure 8: Load capacity improvements in hydraulic and electrical robots (Sources: several secondary sources; Minimum load capacity for the heaviest part used in heavy manufacturing is derived from Industrial Robots: Delphi Forecast of Markets and Technology, 1982, 1985, by the Society of Manufacturing Engineers)

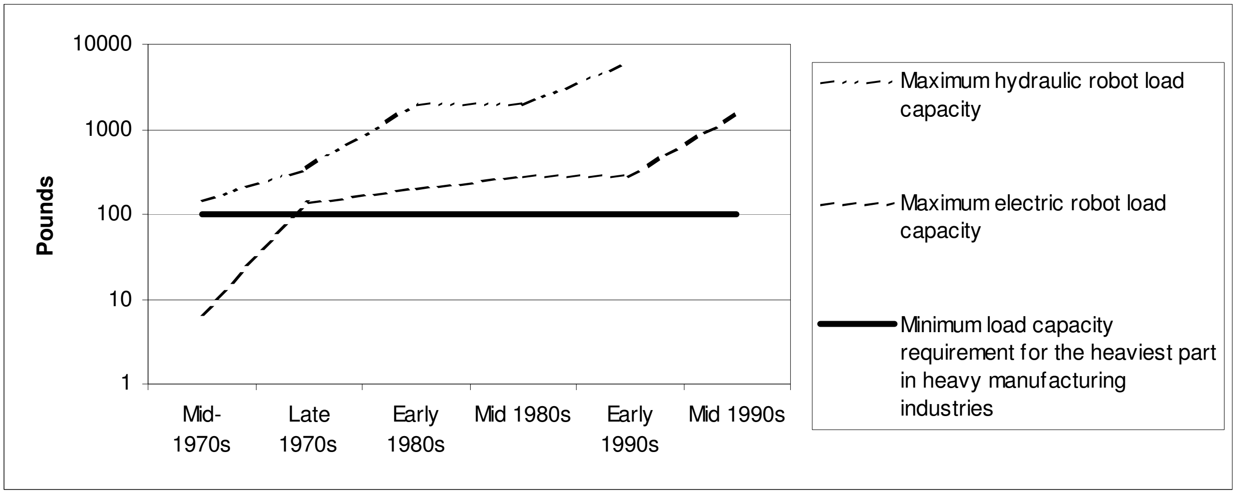


Figure 9: Average price of robots in the U.S. in $ '000s.(Source:USITC Pub.1475, 12/83)

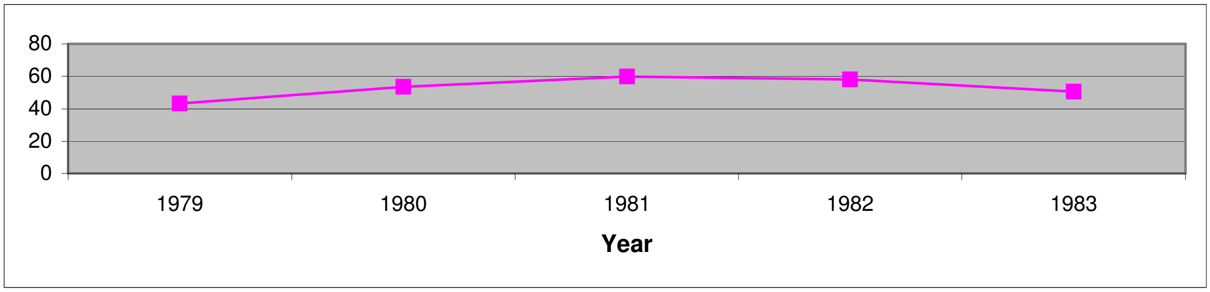


Figure 10: Corporate and Robot sales of major robot manufacturers (in $ MM) (Sources: Annual Reports, Robotics Age, and Industrial Robot, various issues) (Note: Robot sales of ABB and MHI are not available)

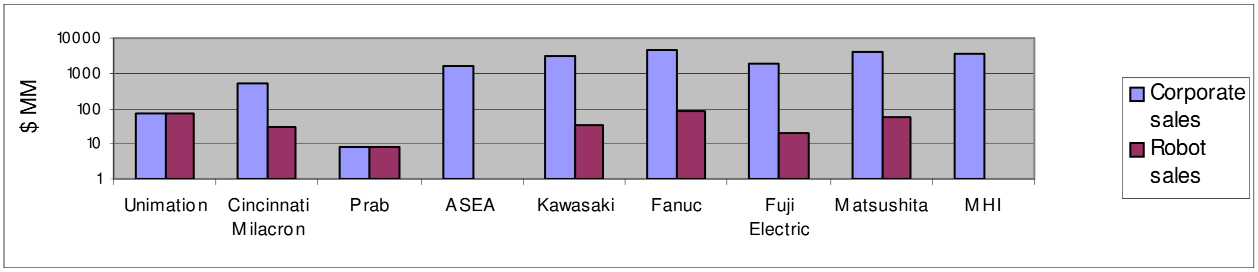


Figure 11: Load capacity of new robots introduced by large manufacturers (Note: CM(H) and CM(E)- Cincinnati Milacron's hydraulic and electrical robots) (Source: Database created from several secondary sources)

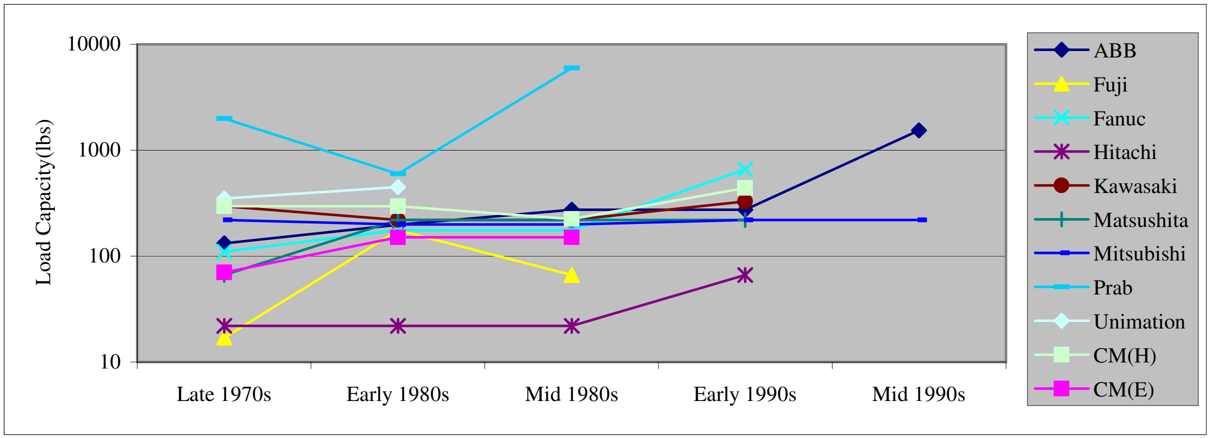


Figure 12: Repeatability of new robots introduced by large manufacturers (Note: CM(H) and CM(E)- Cincinnati Milacron's hydraulic and electrical robots) (Source: Database created from several secondary sources)

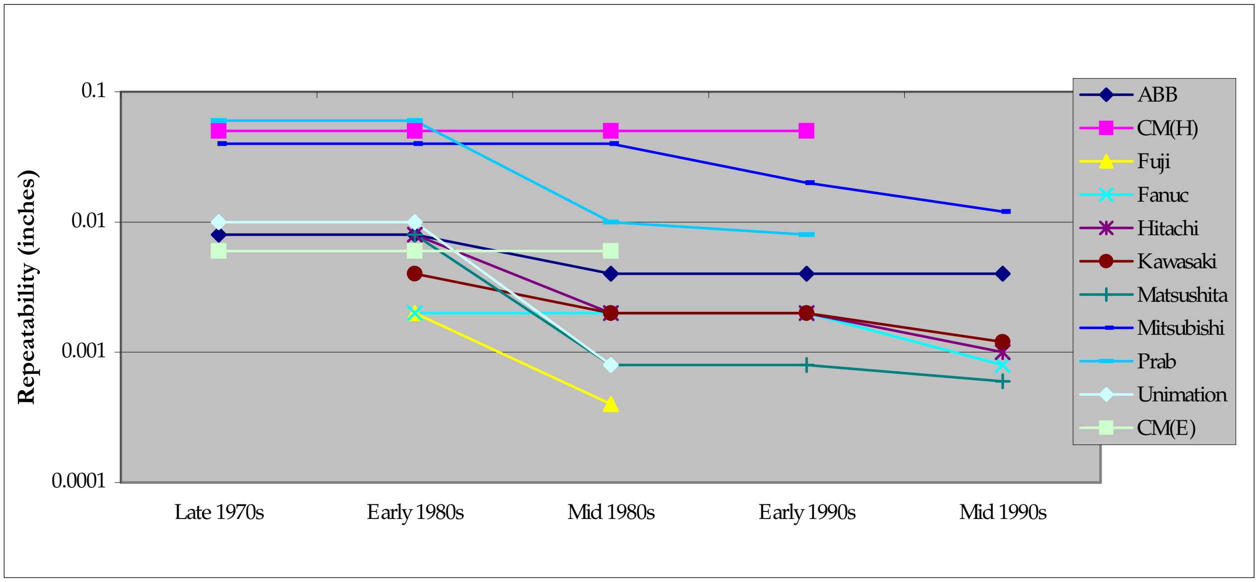


Figure 13: Electrical control systems patents assigned to Robot manufacturers during 1970-1985

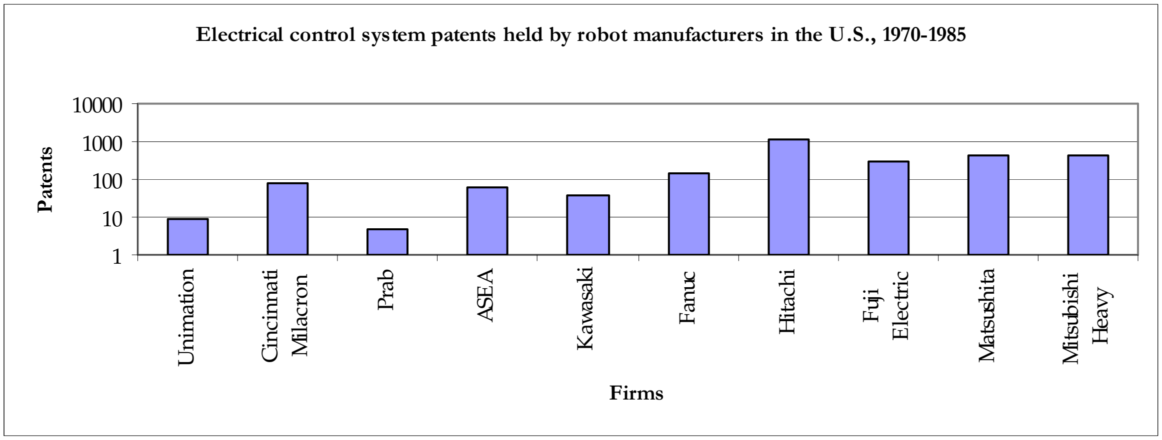
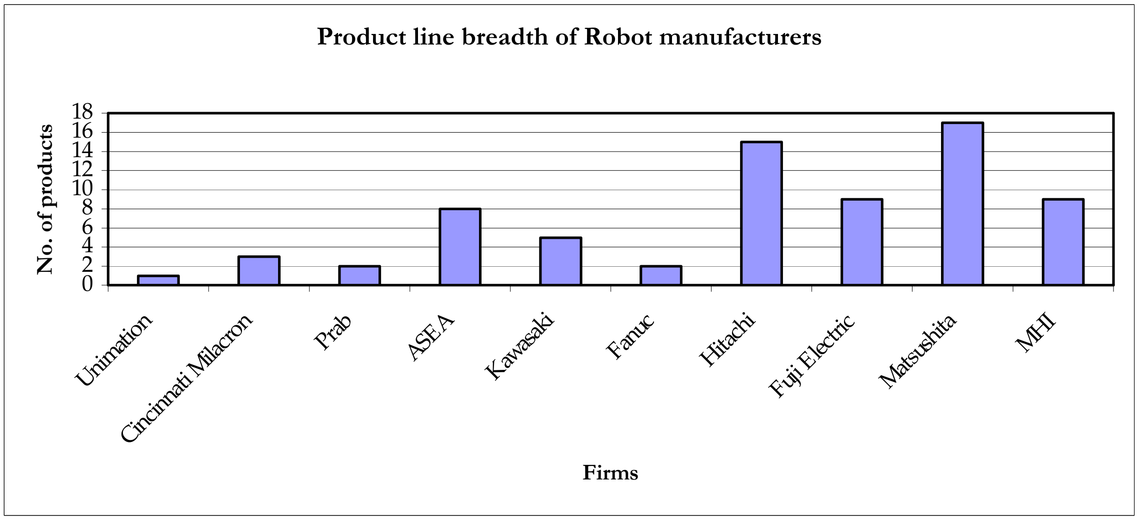


Figure 14: Product line breadth of robot manufacturers in 1980



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