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Views & Comments

Robotics in Industry—Their Role in Intelligent Manufacturing

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1. A view of intelligent manufacturing

1.1. Intelligent manufacturing: The coupling of technology and industrialization

A perspective on intelligent manufacturing can be gained by examining the development stages of modern industrial manufacturing [1]. The use of steam engines as prime movers around 1784 marked an essential step of the First Industrial Revolution (Fig. 1), although an early crude form of the steam engine was invented 50 years earlier by Thomas Newcomen. James Watt invented a separate condenser as a cooling cycle to increase the efficiency of steam engines. Watt also applied a governor (i.e., a mechanical speed regulator) to permit the automatic control of speeds. These technology breakthroughs led to the reliable use of the steam engine. Furthermore, Watt obtained support from a financial investor, Matt Boulton, to produce the new engines in quantity. Technology and industrialization were essential ingredients for the eventual success of the first industrial era. Thus, it might be inferred that a successful development stage is marked by the coupling of technology and industrialization. In the same way, intelligent manufacturing is supported by the integral efforts of information technology and industrialization. In fact, China defined its China Manufacturing 2025 initiative as encompassing information technology and industrialization, in the same spirit as the First Industrial Revolution [2].

1.2. The Second and Third Industrial Revolutions: Mass production and logic control

In the Second Industrial Revolution, mass production led to higher productivity. The basic technology in this revolution was the use of paced conveyor lines that supplemented industrial engineering methods. A manufacturing process could thus be broken into multiple stages, each of which contained a limited number of operations for the worker to perform. Conveyors provided a means to move semi-finished products from one stage to another. As a whole, the overall productivity of the process could be increased. For example, Ford applied this technology along with industrialization to produce millions of vehicles at a lower cost.

The Third Industrial Revolution was represented by the invention of programmable logic controllers (PLCs) in 1969 [3]. Although there were several candidate technologies to represent the integration of computers with machines, the PLC was an easy-to-use and reliable controller to program computational logic. Dick Morley, involved with the production of Modicon, came out with the first working controller based on specifications from General Motors' Hydra-Matic. Modicon was also the first to present ladder logic, which was favored by many automation engineers. Odo Struger and his team at Allen-Bradley, together with the 3i company, developed the PLC and registered the PLC name. (3i was acquired by Allen-Bradley, which later became Rockwell Automation.) Allen-Bradley then wisely invested in automotive applications in order to support the PLC fully as a solid, reliable, and easy-to-use control for automation. PLCs became a billion dollar industry within 10 years of their 1969 debut.

1.3. Industry 4.0: CMIDAN intelligence and robotics

The Working Group of Industry 4.0 presented their report at the Hannover Messe in 2013. The year 2014 marked the beginning of the Fourth Industrial Revolution, with the introduction of using information technology for manufacturing. The intelligent technologies associated with the Fourth Industrial Revolution comprise

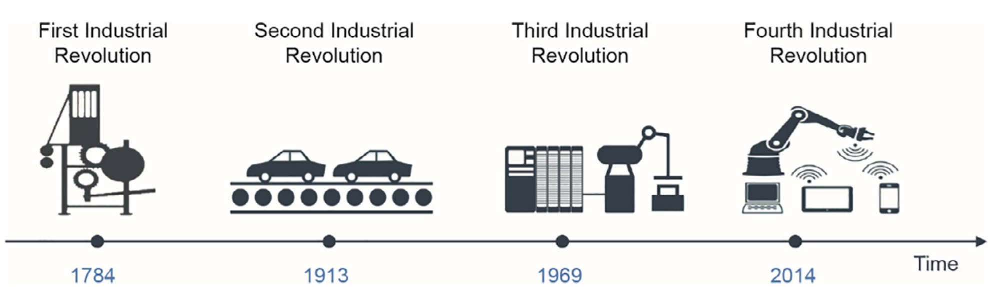

Fig. 1. Industrial manufacturing development stages.

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Fig. 2. Six intelligence areas (CMIDAN) plus robotics. (Credit: Terry Gou, Foxconn Technology Group)

six areas, in addition to robotics (Fig. 2), as classified by Foxconn: cloud computing, mobile devices, the Internet of Things, big data, intelligent analytics, and networks (summarized using the acronym CMIDAN). CMIDAN thus represents intelligence in the virtual world, while robotics represents a mechanism to perform physical tasks in the real world. Together, CMIDAN and robotics can yield additional impact in future intelligent manufacturing. Industrialization efforts have been attempted by many researchers and are continuing.

1.4. Fundamentals for intelligent manufacturing: A One, a Two, a Three

The concepts of Industry 4.0 and intelligent manufacturing can be perplexing to traditional manufacturing enterprises. Some companies wonder where to start, and whether such an investment will really pay off. Such skepticism is natural. In the meantime, other companies have moved ahead and have been eager to adopt intelligence in manufacturing. The results have been mixed, however, because injecting new technologies takes time to internalize and requires adjustments within the company to take effect. Furthermore, it is important to prepare the fundamentals when applying intelligent manufacturing techniques. The fundamental steps can be described using the mnemonic "a One, a Two, a Three" as follows.

1.4.1. A One: One motto

The first step can be summarized with a single catchphrase: Reengineering the intelligent process with modern information technology. Business process reengineering (BPR) was a business management strategy that began in the 1990s [4]. It was intended to reorganize workflow in order to dramatically improve customer service and cut operational costs. A similar reengineering procedure could be adopted for targeted processes in purchasing, operations, engineering, quality, and marketing, utilizing the six intelligent technologies summarized by CMIDAN, along with robotics. This procedure would call for the various departments to rethink and revitalize themselves in light of the new technologies encompassed by CMIDAN in combination with robotics. A pilot project could be planned for demonstration and to tune the process.

1.4.2. A Two: Two basic elements

The second step comprises two basic elements: ① useful data as the source of intelligence, and ② easy-to-use analytics tools to help move toward intelligence. Data provides the basic ingredients for formulating intelligence, with accurate timely data as the key. An excess of unusable data is like noise, without value. Therefore, useful data collection is a basic element of intelligent manufacturing. Analytics tools should be easy to use, in order to allow users to create their own intelligent algorithms from domain knowledge. At the start, analytics can be simple, such as using statistical computations and simple control algorithms. It is always beneficial to have manufacturing engineers gain confidence and perceive the potential value of intelligent manufacturing from the initial data and analytics. After the engineers gain experience, more sophisticated analytics and tools exploring the use of artificial intelligence can be added.

1.4.3. A Three: Three activities

The third step comprises three activities: ① improving interconnection at the data-generation layer, ② applying analytics processing and displays, and ③ using computer-aided tools.

Regarding the first activity, the bottom control layer in a manufacturing system includes robots, computer numerical controls (CNCs), sensors, grippers, and various control devices. This is a core data-generation layer. In factories that were built during the Third Industrial Revolution, many of the machines in this layer already have communications capabilities, albeit with limited data transfers as compared with Industry 4.0 systems. In the intelligent manufacturing era, data generation and transfer capabilities are enhanced. This layer uses more modern sensors, such as high-resolution video imaging (e.g., 8000 pixels per line) and force, torque, inertial, touch, vibration, and temperature sensors to capture manufacturing actions. Data-transmission hardware, data format, and transmission protocols will require upgrading to allow reliable and secure free-flow of data at the data-generation layer.

The second activity comprises applying analytics processing and displays to the upwardly transmitted data as a basis for useful actions. The "intelligent" part of manufacturing lies in this analytics activity. As shown in Fig. 3, control actions are performed to better tune the process. With more data and more powerful analytics, as shown at the top of the figure, the analytics can make predictions to enhance the process. For example, analytics in intelligent machines can be used to send messages ahead for predictive maintenance, thus reducing the risk of potential machine failure [5]. Product data trends can be collected and analyzed in an intelligent manufacturing system so that zero-defect production can be maintained. The use of large quantities of data and

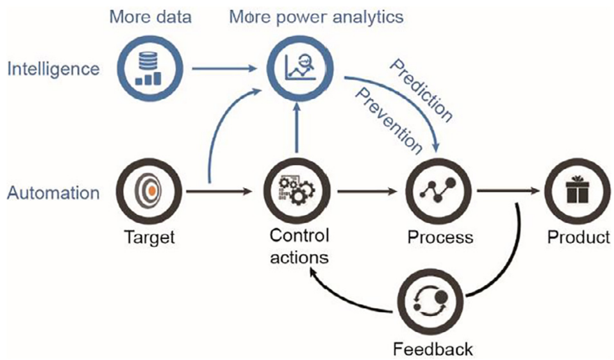

Fig. 3. The use of intelligence to predict changes.

ever-increasingly powerful analytics tools may require cloud services in parts of the system.

The third activity involves the use of computer-aided tools. A holistic intelligent manufacturing system includes the design and planning processes as part of manufacturing. The use of design tools such as computer-aided design (CAD), computer-aided manufacturing (CAM), and product life management (PLM) systems can help to retain knowledge, reduce errors, and provide quicker response. Data collected during production can be used to improve designs for the next generation of products. Manufacturing data can also be communicated with the manufacturing execution system (MES). The CAD, CAM, PLM, and MES systems wholly complement an intelligent manufacturing system.

1.5. Industrial automation progression

Although an automation system can be designed for a particular case requirement, it would usually take several generations of improvements to reach high performance and high reliability. Knowledge gained from each generation will help to optimize designs. The general automation process can start with a single cell; next, a line of automation cells can be linked together for higher throughput. The whole production floor can then be integrated with automation lines and automated material transfers. Finally, the automated factory can become a "lights-out factory," meaning that no human presence is required. Even then, the factory will not remain the same forever. Modifications and enhancements (e.g., applying modern sensors and analytics) must continually be made to keep the factory up to date and to meet new challenges.

1.6. Challenges for flexibility, reusability, and fast ramp-up

Continuing challenges present themselves in intelligent manufacturing in terms of flexibility, the reusability of equipment, and fast ramp-up (and -down). When setting up automation systems, the standard approaches have been to use PLCs along with motion devices, input sensors, and output actuators. When intelligence is added in the form of the CMIDAN intelligent technologies, it will be possible to devise new approaches to meet higher goals of flexibility, reusability, and fast ramp-up. These new approaches may call for an increasing use of higher level system modules, which will provide intelligent capabilities as well as speedy implementation possibilities. Industrial robots would be, in essence, a module for flexibility, reusability, and fast ramp-up. Thus, the combination of CMIDAN technologies and robotics can drive intelligent manufacturing, with further extension to intelligent living.

2. Robotics in industry: Playing a role in intelligent manufacturing

As Joseph F. Engelberger, the father of robotics, commented: "An automated machine that just does one thing is not a robot. A robot should have the capability of handling a range of jobs in a factory." The range of jobs that a robot can handle continues to increase with advances in control, actuation, and sensing. However, successful application must be driven by economics.

2.1. Continual evolution is required in robotics

In 1959, Joe Engelberger and George Devol introduced the first Unimate robot to a die-casting plant in Trenton, New Jersey [6]. This robot caught the attention of General Motors, who wanted to try to use this early robot to do spot welding. The tooling development and application trials took years; finally, the first major installation of 17 Unimate robots to do spot welding was unveiled at the Lordstown, Ohio plant in 1969, 10 years after the founding of Unimation. The installation was a great success, having been built on a considerable amount of hard work in order to achieve such a breakthrough. Plans for subsequent installations were made soon afterward. However, Unimation's competitors were also at work. By 1981, electrically powered robots were preferred over the hydraulic Unimate robots due to their maneuverability and maintainability. Eventually, Unimate robots disappeared from the automotive spot-welding scene. A lesson learned was not to dwell on the success of a single early product, but to keep on reinventing. Today, automotive spot welding has evolved into a systems business. The giants in this business have evolved many times in order to stay in the arena.

2.2. PUMA: A retired robot with a 40-year legacy

In 1977, Engelberger bought Vicarm, a company founded by Victor Scheinman that builds electric robot arms controlled by minicomputers, and renamed it Unimation West. He further developed Vicarm's design into the Programmable Universal Machine for Assembly (PUMA). PUMA was smaller and more agile than the Unimate, and performed well in trials for assembly tasks. PUMA was also linked with vision systems and automated conveyors to perform conveyor-tracking and bin-picking tasks. Such intelligent uses of robots integrated with vision systems became benchmark cases for many years [7]. PUMA became the textbook example for robotic manipulation and controls, and its kinematic design is still popular 40 years later.

However, although PUMA was popular due to its dexterity and programming capability, its intended entry into the assembly market fell short of expectations. During the same period, a simpler and less expensive robot named the Selective Compliance Assembly Robot Arm (SCARA) was applied much more in industry, and was used to produce many video cassette recorder (VCR) players and automotive parts in Japan [8]. A lesson learned was that the cost of automation was a prevailing factor in assemblies. Although extra articulation and intelligence was helpful, economics ultimately prevailed. In current and future assembly applications, this basic economic factor will not change. In addition, the size of the robot matters for small-parts assemblies—the smaller the better.

The idea of a robot working side by side with humans was initially conceived as an application for PUMA, although it did not work out at the time. Today, the technologies of a collaborative robot are more feasible, given the necessary features of small size, light weight, easy programmability, safety, and dexterity. However, assembly operations still require a lower cost with higher throughput. Assembly automation is a much more formidable task than many pioneers in the field of industrial robotics had anticipated. The bottom-line attraction for robotics in assemblies remains one of economics rather than appearance.

2.3. System-integrated robots

Thanks to universities teaching robotics courses for many years and the publication of many textbooks on robotics, the knowledge of writing computer codes to control robots was widely propagated [9]. In addition, many open-source programs and tools became available, lowering the entrance barrier to controlling a robotic device. However, there is a significant difference between being able to robotically move mechanisms and establishing an industrial robotics business. The traditional robot makers built solid reputations in support, application development, training, and cost-downs with their suppliers. To compete with traditional robot makers, opportunities are available to use robots with special system-integrated features to perform application tasks (Fig. 4). Although system-integrated robots (SIRs) may have lower flexibility, they can realize a higher throughput and a lower cost than standard robots. SIRs are thus positioned in between specialized machines and traditional robots to serve the intended applications.

2.4. Automation robotics for the 3C industry

Products and services related to computers, communications, and consumer electronics are collectively referred to as the 3C

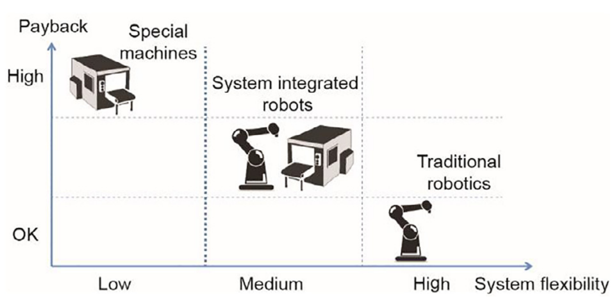

Fig. 4. The positioning of SIRs in terms of payback and system flexibility.

industry. This is a large industrial sector with huge demands on equipment and assembly workers. The recent growth of the 3C industry is exemplified by the increasing use of smartphones, which have radically changed the means by which people communicate.

From a manufacturing perspective, a typical mobile phone product comprises a back cover, front screen, printed circuit boards (PCBs), and interiors. Back covers have progressed from plastics to metals such as magnesium, aluminum, stainless steels, and titanium, and then further to non-metals such as glass, sapphire, and fiberglass. Manufacturing steps for the back cover alone can be in the hundreds, and range from extruding metals, to machining, to polishing, and finally to surface treatments. Robotic automation has been applied in many of the steps in manufacturing the back cover of smartphones that are commonly known as "3D" (i.e., dirty, dangerous, and dull) processes. A unique requirement for a 3C business is fast ramp-ups and fast ramp-downs, which require unusually large manufacturing capacities/capabilities and quantities of machines to go quickly from planning, design, tooling, and testing, to mass production. Typical robotic applications in the 3C industry are shown in Fig. 5(a), and current and potential applications for robotics in assembly operations are shown in Fig. 5(b). Robotics opportunities for the 3C industry continue to be of great interest.

It takes huge capital investments to manufacture the various types of displays for the front screens of smartphones. Many of the display manufacturing processes are performed in clean-room environments using reliable equipment and processes with proprietary knowhow. Further steps in display manufacturing require the precision bonding of glass and touch panels using special-purpose high-precision machines for productivity and reliability. PCBs with surface mount technology (SMT) components are also produced using dedicated machines and systems. For display manufacturing, there are opportunities for robotic systems in various secondary load/unload and material-transport tasks.

2.5. Requirements for robotics in the 3C industry

Assembly has always been perceived as an area with numerous potential robotic applications. As the volume of 3C products increased, production lines were set up along a conveyor line

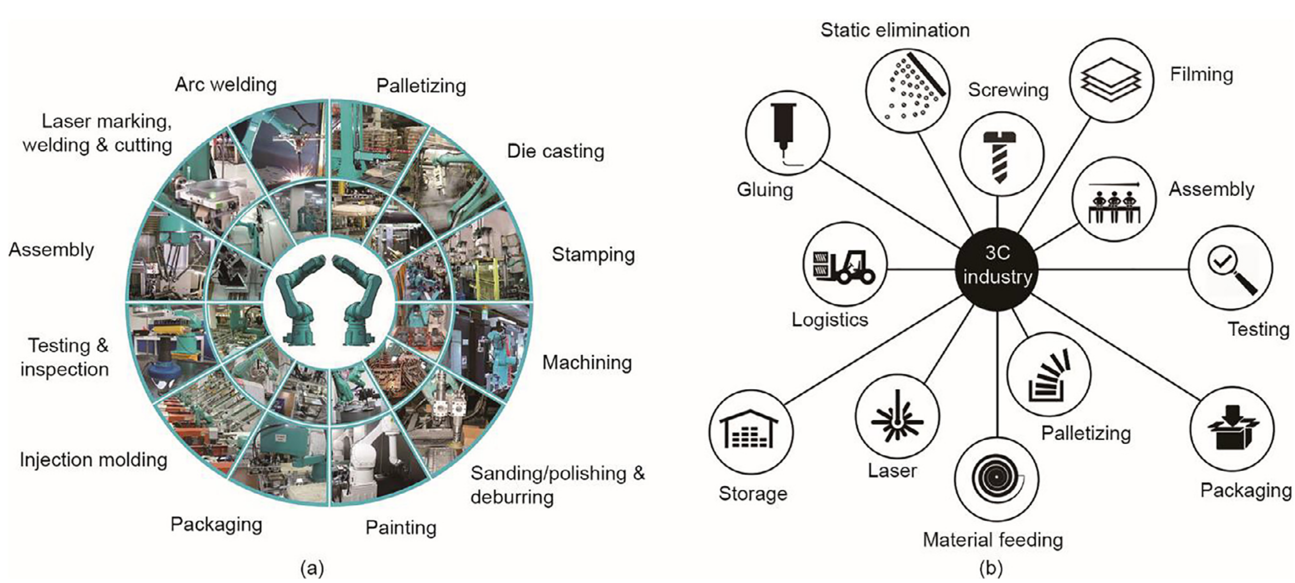

Fig. 5. (a) Typical robotic applications in the 3C industry; (b) current and potential applications for robotics in assembly operations.

where workers performed repetitive but confined tasks per standard operating procedure (SOP). Thus, the mass production method exemplified in the Second Industrial Revolution was upgraded with controls from the Third Industrial Revolution. Like automotive assembly operations, where vehicle parts are currently still assembled by hand in the trim shop, the 3C final assembly operations still largely rely on human workers. With increasing numbers of workers come continuing attempts to add automation as a relief for hiring workers. Human workers offer the advantages of dexterity, quick visual/tactile feedback, and flexibility. The challenges are high for robotic assemblies; however, given the rising costs of labor, opportunities to apply robots to assemblies are increasing.

The other challenge facing assembly plants is floor space. With a large quantity of products to be produced, floor space is at a premium. Thus, automation and robotic systems must be compact in order to save space. Another challenge for robotics in assembly is in sensory abilities. Human workers can use many cognitive abilities such as vision and touch. Abilities such as these are necessary in many tasks in assembly operations. In simple terms, the requirements for the 3C industry can also be summarized in the form of "3Cs": cost, compactness, and cognition.

2.6. Mobile robots and the mobile robot system

Automated guided vehicles (AGVs) in factories help carry parts to be assembled and perform flexible tasks on command. These vehicles could be reprogrammed for other tasks as the products and processes change. Such characteristics would qualify them as robots or, more specifically, as mobile robots (MRs). A typical "lights-out factory" would include MRs to help move products and components (Fig. 6). MRs communicate and work in conjunction with automation lines and manipulator robots, thus enabling the whole factory to be automated. In such cases, a mobile robot system (MRS) can command the planning, calling, scheduling, and event-handling functions. MRs can be deployed in many forms and sizes, with customizations to suit the special needs of each plant. As in assembly automation, cost is a strong influence on the type of MR and MRS to be adopted. The MR and MRS arenas are wide open, encompassing high-end, highly functional systems as well as low-cost, bare-bone systems. The amount of service and support can vary, from closely attended support to no-frills or even no-support operations. This is still a fragmented market, ready for innovations and business models. Both MRs and MRSs complement automation robotics in intelligent manufacturing.

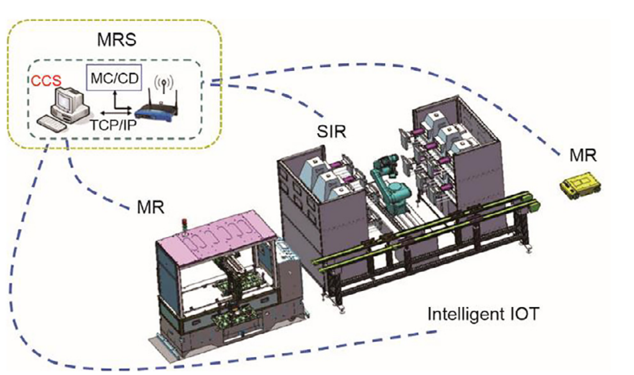

Fig. 6. A smart factory with MRs and an MRS. CCS: central control system; CD: cloud data; IOT: the Internet of Things; MC: master computer; TCP/IP: Transmission Control Protocol/Internet Protocol.

2.7. Industrial robot intelligence: Distributed and Internet-enabled

Science fiction stories and movies have stirred up public fascination with robots having high-intelligence thinking and moving like humans. Industrial robots will not meet such expectations of intelligence. Although very special computers or robots may be able to win chess competitions or drive cars automatically, the reality is more like the Moravec's paradox: "It is comparatively easy to make computers exhibit adult-level performance on intelligence tests or playing checkers, and difficult or impossible to give them the skills of a one-year-old when it comes to perception and mobility" [10]. In industrial robot applications, many of the tasks to be performed by robots are relatively confined physical movements that are primitive compared with the gait mobility currently under research. For industrial applications, the intelligence of industrial robots can be distributed such that the local processing of the sensors, vision images, motions, logic, and communications collaboratively produces the desired system-level performance. Start from here, various agents in a system can communicate with each other to produce group intelligence that can be linked by high-speed serial communications—thus making the robots Internet-enabled.

2.8. Searching for gold at the end of the rainbow, but facing brutal realities

Fig. 7 shows a process flow from automation component suppliers, to automation robotics, to the factory, and finally to the end customer. Overlapping the process is a colorful rainbow. When the rainbow appears, the storied leprechaun busily hides pots of gold at the end of the rainbow, and people search for them. Some metaphorical "pots of gold" (i.e., high-profit applications, products, and services) may lie between the manufacturing factories and the end-customers, such as e-commerce retailers and advertising mediums. At the other end, other "pots of gold" may be found between the automation component suppliers and the automation/robotics system integrators, such as system module suppliers. A metaphorical hypothesis of robotics might be: "Intelligence elevates the rainbow to be high and beautiful, but the real gold lies at the ends of the rainbow." In other words, intelligence may make the manufacturing equipment and process beautifully efficient, but the big profits are at the intermediaries. Thus is the brutal reality for manufacturing automation.

In summary:

(1) In their search for "gold," some pioneers in the robotics industry hoped to locate the ultimate applications of robotics. However, such applications are not easily found. With persistent cultivation and craftsmanship, it is possible to come close to finding such applications, but considerable and persistent effort is required in order to obtain real results.

(2) In intelligent manufacturing and industrial robotics, helping to solve process issues in manufacturing is the priority. It can be said that the greatest contribution of robotics has been in the productivity improvement of the manufacturing industries.

(3) Programs to promote manufacturing automation such as the China Manufacturing 2025 initiative speed up automation and expand it to reach more places and broader segments of the economy. Such initiatives could be a bonanza for automation equipment makers and component suppliers. It will take hard work and craftsmanship to produce quality components and modules.

(4) Large manufacturing enterprises have more resources to take on new technologies than small manufacturing enterprises. In order to gain access to new technologies and speed up automation, large manufacturing enterprises are likely to develop their own robots, form alliances, or plan acquisitions in the robotics arena.

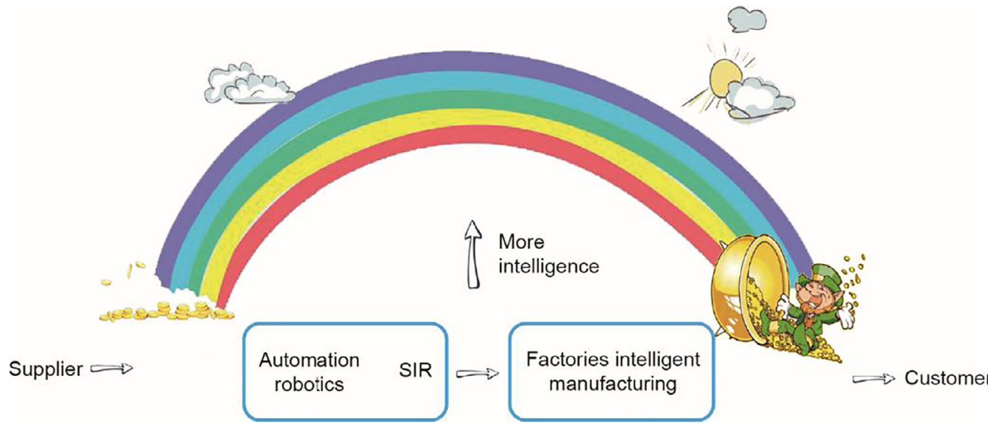

Fig. 7. Gold at the end of the rainbow.

(5) The spread of the Internet of Things is emerging as the greatest opportunity for non-traditional robot entrepreneurs. Increasingly powerful microprocessor-based controls and cognitive devices provide innovative opportunities for non-traditional robot makers. Adding artificial intelligence to Internet-enabled robots would open up new applications.

(6) The 3C industries provide opportunities for ideas on novel robot systems or SIRs with distributed intelligence in order to meet the requirements of cost, compactness, and cognition. Linking through the Internet or cloud to add artificial intelligence capabilities could expand SIR applications.

In the 1980s when robotics was all the rage, there were over 200 robot companies in the United States; then the number of companies dwindled [11]. Today, however, there are thousands of robot companies in China alone. People are attracted by the potential growth of robotics everywhere. A focus on craftsmanship and fundamental skills can help to steer this industry toward healthy long-term growth.

3. Summary

In *Through the Looking-Glass* by Lewis Caroll, the Red Queen says to Alice: "Now, here, you see, it takes all the running you can do, to keep in the same place." Developing and implementing robotics in industry will not be easy. For robotics companies to remain in intelligent manufacturing will take a great deal of "running" just to hold one's ground! All of the explorations in robotics and intelligent manufacturing in the past decades have revealed a simple truth: Although craftsmanship takes time to develop, its impact will remain.

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