

Review:

Development of SCARA Robots

Kazuo Yamafuji

The University of Electro-Communications
1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan
E-mail: kazyama@r2.dion.ne.jp

[Received November 20, 2018; accepted December 3, 2018]

The presentation on SIGMA robot for assembly by A. d'Auria at the 7th International Symposium on Industrial Robots (ISIR) held in Tokyo in October 1977 made an immense impact on engineers studying assembly automation in Japan. The 1970s witnessed the shift from the mass production of a few types to limited production of a wide variety of products in Japan, and research started for a production system with a quick response to a given type of products and change in a quantity of production. Professor Hiroshi Makino of Yamanashi University was stimulated by SIGMA and got an idea for a robot with Selective Compliance Assembly Robot Arms (SCARA) and started working on the design for prototype 1 two months after the presentation. Further, he organized the SCARA Robot Consortium with Yamanashi University and thirteen domestic companies for three years, from April 1978 to March 1981, and had success in the development and spread of the SCARA robot in the assembly work. After the 1980s, the SCARA robot became one of the de facto standards of industrial robots in the world. In 2019, it is estimated that the SCARA robots will compromise 30% or more of industrial robots working all over the world. The author was one member of a research group as an associate professor, in Yamanashi University, and believes that it is extremely effective to discuss the needs for research and development of the SCARA robot and technological solutions thirty years after the establishment of JRM.

Keywords: assembly automation, robot for assembly, SCARA robots, consortium, application

1. Needs and Problems of Robot for Assembly

In 1968, the Committee for Automatic Assembly (CAA) of the Japan Society of Precision Engineering (JSPE) was established and began research and development on assembly automation and started spreading knowledge of the technology. The committee consisted of about 180 members having interest in automatic assembly: engineers in companies, and researchers in universities and research institutes. The committee researched and developed technical problems by exchanging infor-

mation, and also carried out the diffusion and edification to the outside by holding lecture meetings and publishing technological materials.

When the development of the economy in Japan experienced a boom in the 70s and the national income increased, the needs of consumers changed. In response to that, a shift from mass production of a few kinds of products to limited production of a wide variety of products occurred, and the shift to the limited production of a wide variety of products began for vehicles, electronics, and mechanical products.

When an oil shock occurred in 1973, a rise of wages by thirty percent or more per a year occurred. The shift to a flexible manufacturing system (FMS) and the rise of wages corresponding to the limited production of a wide variety of products accelerated the automation of the assembly process of products and production technologies were variously developed.

In this case, a special-purpose machine for automatic assembly was changed to flexible assembly to easily allow a change in its production target, it was important to exchange models for a short time, therefore general machines for automatic assembly were developed and FMS to make tool changing or retooling free was put to practical use. However, it was thought to be unattainable in the near future to realize general robots for assembly due to high cost/performance.

Technological problems prohibited the attainment of the speed and precision required for assembly work with the robot technology at that time, and it was thought to be difficult to replace even work capable of being operated by a human collaborating with a robot. Human beings have excellent intelligence, sensors and dexterity, and not only execute work given but also respond to defects of parts or of assembly, abnormality of peripheral equipment and can perform visible inspection and remake defective products. It was thought that robots could only correspond to works that were operated by human beings.

Developing a robot for assembly in a situation where industrial robots were used at that time was expensive in viewpoint of range of functions, costing at least 50,000 USD. In the electrical, electronic, mechanical, and precision technology industries, a lot of assembly tasks were machined by young employees, or part-timers in many cases. If their annual wages were assumed to be 10,000 USD and their work was done in 3 shifts, the in-



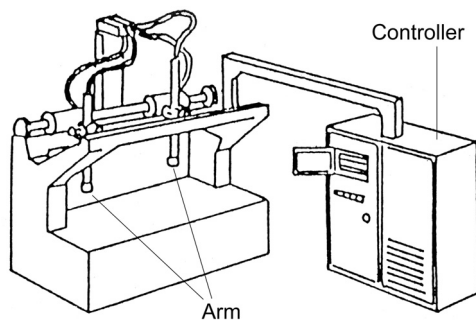


Fig. 1. SIGMA robot.

roduction of the robot could be worth 30,000 USD.

2. Impact of Sigma Robots and the Appearance of SCARA Robots

Any engineer in Japan was surprised to see the operations of the assembly robot, SIGMA (Fig. 1), presented by d'Auria (Olivetti Inc., Italy) [1] at the 7th ISIR held in Tokyo in October 1977, and was shocked at how quickly it realized the goal for robots in assembly as mentioned above.

However, Dr. Hiroshi Makino started to design a robot for assembly on the basis of a unique idea two months after the presentation of SIGMA. Several years ago, one of the research themes presented by him was assembly center (AC). This was assembly by applying an idea of a machining center (MC) for complex processing as the latest technology in machine tools and using a plurality of parts that were automatically supplied with one machine.

It was thought that it was effective for the limited production of a wide variety of products if it made it possible to perform various complex assemblies with the same assembly station using AC. He mentioned that it took about thirty seconds to assemble one part with the AC, and data proving the availability of the machine were obtained [2].

It was obvious in research that various types of parts could be assembled just by changing the software, which making it possible to simultaneously have the versatility and productivity with a fast robot. At the end of December 1977, when the author went to Dr. Makino's office, he showed me a drawing of the basic idea of the SCARA robot. The drawing indicated a three-axis robot with a folding screen structure having horizontal articulated double jointed arms and a vertical axis: the Z-axis.

The robot had the arms corresponding to the right arm of a part-timer, as is typical. It had a simple structure with features to be easily moved in the horizontal direction but be more difficult to move in the vertical direction.

The horizontal two-joint-link mechanism with features for a SCARA robot has been conventionally used for a dental drilling machine, an automatic arc-welder, and a jig borer. However, nobody thought that the mechanics could be used for robots in assembly.

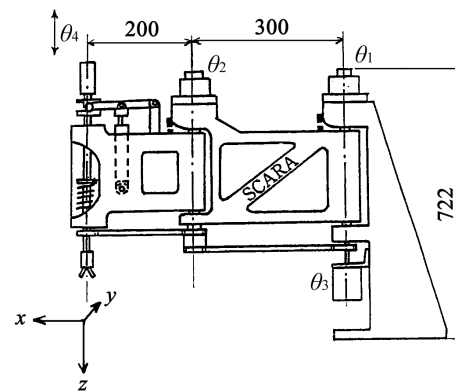


Fig. 2. SCARA robot drawn by Dr. Makino.

3. Concepts and Features of SCARA Robot

3.1. Concepts of SCARA Robot

The robot for assembly, as the main body of an assembly center should be operated accurately at high speed, and the operational position should arbitrarily be changed by a software. Further, the price of the robot should range from 20,000 to 30,000 USD per robot.

Dr. Makino described the time when the concepts of the SCARA robot were born as follows [3]. That is, he said, "it could not be accurately mentioned when and how a new mechanism was formed in the head and it was thought to be right that the concepts of the new mechanism were, perhaps, in the head first and were gradually fixed through various experiences. I knew there were a polar-coordinate robot and a multi-articulate robot when making an LEGO machine. I have analyzed a robot mechanism before and therefore really knew a working area was wider as the number of rotary joints was larger. However, I believed that a Cartesian-coordinate type as SIGMA had high rigidity and was advantageous for speed-up."

"Once actually making the robot, the rigidity of the Cartesian-coordinate type is not so high. A tool is overhung from an XY-table and press fitting force is consequently applied and moment works, and the XY-table is to be broken. The rigidity in the X-direction or Y-direction might exist, however, is not required, I think. It might be better that there is compliance, or it might work rightly that low rigidity in the XY-direction might be better, though high rigidity in the Z-direction might be better. As a result, an idea of the SCARA robot with a folding screen structure is born." Selective compliance that the rigidity is low in the XY-direction and the motion in the Z-direction is hard, is the biggest feature of the SCARA robot that will be widespread in the world in robots for assembly.

3.2. Structure and Features of SCARA Robot [4]

Figure 2 shows a horizontal multi articulate-type robot for assembly designed by Dr. Makino. Arbitrary plainer

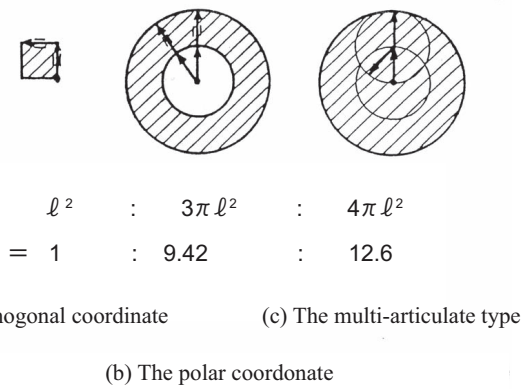


Fig. 3. Comparison of working area due to types of robot with two joints.

coordinates are given at an edge by rotational angles θ_1 and θ_2 of two arms combined by a joint. The insertion direction (Z-direction) is vertical to the plane.

To rotate the first arm, a motor for θ_1 of 200 W is mounted at the shoulder part. To rotate a second arm, a motor for θ_2 of 50 W is provided at the edge of the first arm, i.e., an elbow joint. Harmonic reduction gears at a reduction ratio of 1/80 are built into both motors.

A rotary encoder is attached to both motor shafts for position feedback. Further, a tacho-generator is mounted on the motor for the first shaft for velocity feedback.

When a plainer position is given to a tool point that is below the top end of the second arm with rotation of the first and second shafts, the direction of the tool is varied depending on the angle of the second arm. To prevent the change, the rotational angle θ_3 of the tool axis is controlled with a stepper motor. The up-and-down motion of the tool axis (Z-axis) represents on/off operation with a pneumatic cylinder. As mentioned above, prototype 1 is a robot having three axes for rotation (θ_1 , θ_2 , and θ_3) and the Z-axis (for up-and-down motion).

3.3. Structural Features of SCARA Robots

- (1) Structure of the selective compliance: the SCARA is named after “Selective Compliance Assembly Robot Arm.” What is meant by selective compliance is that in the lateral direction, it has high flexibility and easy deformation, while in the vertical direction, it has high rigidity and difficult deformation. These features make it possible for the arm, when fastening screws and inserting pegs into holes, for example, to carry out automatic assembly by pressing its vertical axis even when some discrepancy exists in a lateral direction.
- (2) The working area is wide: as shown in **Fig. 3**, a multi-articulate robot has a working area of 12.6 times that of a Cartesian-coordinate robot and 1.34 times that of a polar coordinate robot.
- (3) The mounting area is narrow: a transfer conveyor is

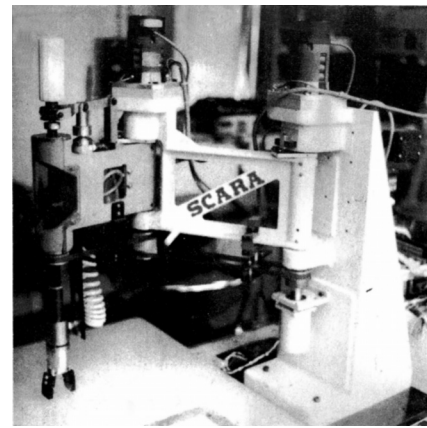


Fig. 4. SCARA robot prototype 1 (Fujitsu).

arranged around the robot and it is possible to structure a multi-robot system with a multi-station.

- (4) The insertion force is large: the rigidity in the Z-direction (vertical direction) is large and large insertion force can therefore be applied.
- (5) The weight for transportation is large: payloads of up to 30 kgf are transportable by prototype 1.
- (6) No consideration for gravitational balance: the motion direction of the arms is in the horizontal direction, and therefore is orthogonal to the direction of gravity. There is no influence from the load and gravitational force of the arm itself, unlike with other robots.
- (7) Not only wrist compliance [5] but the selective compliance structure is formed as the whole arm. Therefore, the compliance features are not changed even when changing a tool part.

3.4. Motion Control

In July 1978, SCARA robot prototype 1 (**Fig. 4**) was manufactured based on **Fig. 2**. Its motion is extremely fast, with a maximal speed of 1 m/s and a maximal acceleration 1 m/s². On the other hand, another robot could run slowly. The SCARA robot runs fast at the start as it is driven from the start to the end of the motion of the arms by motion curves based on cam curves [6, 7].

The first and second arms are driven by software cam curves called NC-2 velocity curves. The NC-2 velocity curve was born as a best virtual cam curve from the research of Dr. Makino, and later became a standard driven curve of SCARA robots for a long time.

Figure 5 shows the NC-2 velocity curve. In **Fig. 5**, a relationship is given between A (acceleration), V (velocity), S (displacement), and T (time). The NC-2 curve is excellent as a motion curve of the robots in point that deceleration period is 2 while acceleration period is 1 and residual vibration is therefore small even if the speed is high, and it is possible to correspond to small payload to high one.

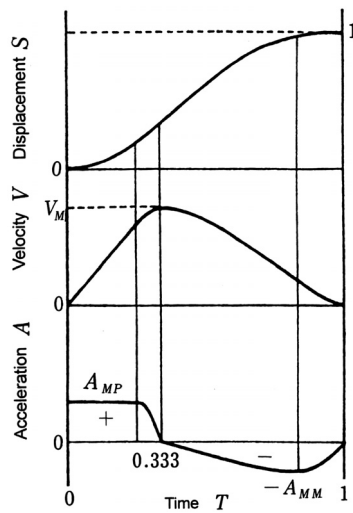


Fig. 5. NC-2 velocity curve.

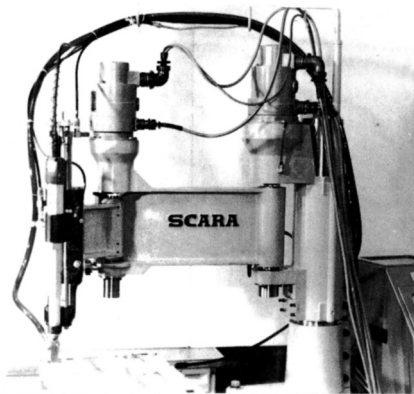


Fig. 6. SCARA robot prototype 2 (Nitto Seiko).

4. R&D Consortium of SCARA Robots

A proposal for joint industry-academia research on a multi-client basis was offered based on some conceptual drawings to a dozen or so companies of CAA of JSPE.

A R&D consortium for SCARA robots was launched by Yamanashi University (professor H. Makino and associate professor K. Yamafuji (the author)) and thirteen Japanese companies (Fujitsu, Nitto-Seiko, NEC, Pentel, Sankyo Mfg. (now, NIDEC), Telmec (now, Tokyo Electron), CKD, Yamaha Motors, Pioneer, Tenryu Seiki, Ultrasonic Industry, Hitech Seiko, and NAIS) in March 1978 for an intended period of three years from April 1978 to March 1981.

SCARA robot prototype 1 shown in Fig. 4 was made by Fujitsu in July 1978. Fig. 6 shows SCARA robot prototype 2 fabricated by Nitto-Seiko, which is more improved than prototype 1.

Figure 7 shows a flowchart of development of the SCARA robot with the consortium. From 1980 to 1981, various types of the SCARA robot were put on the market one after another, and the mass media talked about them

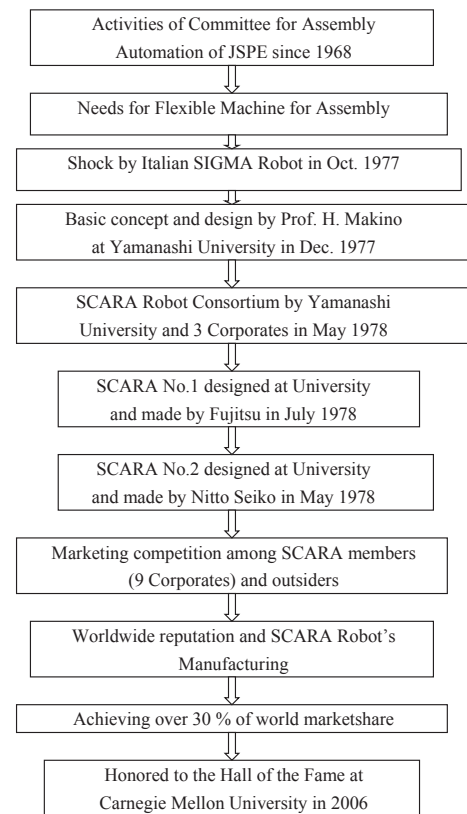


Fig. 7. Flowchart of development of SCARA robot.

as major news items [8].

The consortium was terminated in March 1981. In 1982, IBM announced that it would obtain from Sankyo Seiki a robot named “Sankyo Skilam” on an OEM basis and put it on the market as IBM 7535. This was the first international recognition of the SCARA robot, and triggered a new leap forward.

In 1982, John Hartley wrote, “More startling, perhaps, was the announcement that the IBM was to sell Sankyo Skilam robot in the USA as the IBM 7535. Most of Japanese robots were based on overseas designs. The exception, of course, is the SCARA robot. The Skilam is one of the SCARA group of robots developed at Yamanashi University by professor Hiroshi Makino for assembly [9].”

Figure 8 shows a model of the Sankyo Skilam and its working area, respectively. A. J. McKillop of IBM (United Kingdom) presented an application of IBM 7353 featuring the insertion of a typewriter key into a carrier [10].

In 2008, Mr. Kazuyoshi Yasukawa, president of Nidec Sankyo Inc., who had designed the Sankyo Skilam as an engineer in his middle twenties, said “IBM’s objective was to equip the robot with the industrial computer produced by IBM and sale the complete product. Over 100 robots have been exported monthly for 6 years, and over 7,000 robots in all.”

deficiency, and complete practicality.”

It is no doubt that the SCARA robot can be one of the industrial robots contributing to human beings in the future for utility as a tool for production automation and large technological impacts.

In 2006, the SCARA robot was honored as the one of the first Japanese robots together with ASIMO Humanoid by HONDA (2004) and AIBO by SONY (2006) dedicated to the Hall of the Fame at Carnegie Mellon University, US [11].

References:

- [1] A. d'Auria, "SIGMA Assembly Robot Application," Proc. of 7th Int. Symp. on Industrial Robots, pp. 317-322, 1977.
- [2] H. Makino, "NC assembly centre," J. of Japan Society of Precision Engineering, Vol.41, No.3, pp. 250-255, 1975 (in Japanese).
- [3] H. Makino, "Assembly process," Automation, Vol.24, No.1, pp. 18-22, 1979 (in Japanese).
- [4] H. Makino, M. Murata, N. Furuya et al., "Research and Development of SCARA Robot," Preprint of 47th Meeting of Special Committee for Automatic Assembly of Japan Society of Precision Engineering, p. 12, 1980 (in Japanese).
- [5] J. L. Nevins and D. E. Whitney, "What is remote center compliance and what it can do?," Proc. of 9th Int. Symp. on Industrial Robots, 1979.
- [6] H. Makino, "Kinetics of Automated Machines," Nikkan Kogyo Shinbunsha, 1976 (in Japanese).
- [7] H. Makino, "Universal Cam Curve and its Application," Bulletin of Yamanashi University, Vol.28, pp. 48-58, 1977 (in Japanese).
- [8] Staff writer, NIKKEI Mechanical, p. 44, May 25, 1981 (in Japanese).
- [9] J. Hartley, "The Japanese Scene: Applications diversify," Industrial Robot: An Int. J., Vol.9, Issue 1, pp. 56-61, 1982.
- [10] A. J. McKillop, Int. Conf. on Assembly Automation, p. 267, 1985.
- [11] H. Makino, "Development of the SCARA," J. Robot. Mechatron., Vol.26, No.1, pp. 5-8, 2014.



Name:

Kazuo Yamafuji

Affiliation:

Professor Emeritus, The University of Electro-Communications

Address:

1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan

Brief Biographical History:

1967 Graduated from Yokohama National University

1973 Graduated from Graduate School of Engineering, The University of Tokyo (Ph.D.)

1973 Lecturer, Yamanashi University

1974 Associate Professor, Yamanashi University

1988-2001 Professor, The University of Electro-Communications

Main Works:

- "Useful Robots and Hopeful Robots," Fuji Technology Press Ltd., 2010.
-

The basis of this paper is Chapter 8 of K. Yamafuji, "Useful Robots and Hopeful Robots," Fuji Technology Press Ltd., 2010.