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Discussion

An Investigation Into the Compliance of SCARA Robots[1]

D. E. Whitney.[2] I have read with interest the articles by ElMaraghy and Johns [D1], [D2] on theoretical determination and experimental verification of SCARA robot compliance, and have several comments.

1. The discussion in [D1] on RCC's and IRCC's is cogent and well states the issues. Some clarifications are in order, however. While it is important to choose RCC's carefully in relation to the parts that are to be assembled, it is also important to note what features of the RCC are necessary to consider. Of these, the one not mentioned in [D1] is the absolute stiffness. From the point of view of contact force between parts per unit of positioning error, smaller stiffness (larger compliance) is better. Combining results from [D2] and [D3] we see:

Stiffness of ADEPT robot	162.5 N/mm – 189.4 N/mm
Stiffness of RCC [D4]	16.85 N/mm

This factor of 10 improvement in stiffness of the RCC over the ADEPT is significant, especially since errors on the order of 1 mm are often encountered in small parts assembly. For more information on RCC's, see [D5].

2. Strictly speaking, the robot shown in Fig. 10 of [D2] is not a SCARA robot. As originally defined [D6]; the SCARA is of the form taken by the ADEPT. The robot in Fig. 10 is like a PUMA. Just because it has two parallel axes does not make it a SCARA. If the PUMA is a SCARA, almost every robot could be called a SCARA.

3. Another clarification involves the IRCC. Contrary to what is said in [D1], IRCC's do not contain force sensors but instead contain displacement sensors, usually optical. The IRCC is simply an RCC whose internal displacements are measured [D7]. In fact, even "force sensors" such as those made by Lord, Barry Wright, and JR3, share with IRCC's the same basic operating principle: They are all calibrated compliances whose internal displacements are measured. In "force" sensors, the measurement is usually made by displacement sensors called strain gages. "Force" in both kinds of sensors is then inferred from the measurements by multiplying them by a previously calibrated stiffness matrix, itself obtained by applying known forces and moments and recording the resulting displacements [D8]. The only, though crucial, difference between the IRCC and "force sensors" is that the former are many orders of magnitude less stiff, affording the advantages of RCC's plus the ability to measure and monitor mating forces. An IRCC can (obviously) also measure the displacements themselves as long as the robot it is attached to is at least 10 times stiffer. The ADEPT qualifies in this respect.

[1] By H. A. ElMaraghy and B. Johns, published in the March 1988 issue of the Journal of Dynamic Systems, Measurement, and Control, Vol. 110, pp., 18–30.

[2] Charles Stark Draper Laboratory, Cambridge, MA 02139.

Additional References

D1 ElMaraghy, H. A., and Johns, B., "An Investigation into the Compliance of SCARA Robots, Part I: Analytical Model," ASME Journal of Dynamic Systems, Measurement, and Control, Vol. 110, Mar. 1988, pp. 18–22.

D2 ElMaraghy, H. A., and Johns, B., "An Investigation into the Compliance of SCARA Robots, Part II: Experimental and Numerical Validation," ASME Journal of Dynamic Systems, Measurement, and Control, Vol. 110, Mar. 1988, pp. 23–30.

D3 Whitney, D. E., and Rourke, J. M., "Mechanical Behavior and Design Equations for Elastomer Shear Pad Remote Center Compliances," ASME Journal of Dynamic Systems, Measurement, and Control, Vol. 108, Sept. 1986, pp. 223–232.

D4 The RCC used is typical of those made by Lord Corporation and Barry Wright Corporation.

D5 Whitney, D. E., "The Remote Center Compliance," *The International Encyclopedia of Robotics*, Wiley Interscience, New York, 1988, pp. 1316–1324.

D6 Makino, H., Furuya, N., Soma, K., and Chin, E., "Research and Development of the SCARA Robot," *Proceedings of the 4th Int'l Conf. on Production Eng.*, Tokyo, 1980, pp. 885–890.

D7 DeFazio, T. L., Seltzer, D. S., and Whitney, D. E., "The Instrumented Remote Center Compliance," *The Industrial Robot*, Vol. 11, No. 4, Dec. 1984, pp. 238–242.

D8 Watson, P. C., and Drake, S. H., "Pedestal and Wrist Force Sensors for Automatic Assembly," *Proceedings, 5th Int'l Symp. on Industrial Robots*, Chicago, 1975.

Authors' Closure

The following are comments on Dr. Whitney's remarks and are numbered to correspond with his.

1. The purpose of the analytical model developed in [A1] is to quantify a robot end effector compliance as a function of the arm parameters and characteristics. The ADEPT I is known to be a stiff arm, yet our model applies equally to both soft and stiff SCARA robots.

The first comment reiterates established facts about RCC's. Our analytical model enables the user to estimate the end effector compliance and its variation within the envelope, and assess the need for additional enhancements (using RCC's or other devices) with their attendant cost and complications.

We have applied our compliance model [A1] to an IBM 7576 SCARA robot, which is less stiff than ADEPT I, and obtained very useful compliance maps (to appear soon).

2. The results published in [A3] and used in [A2] were obtained by ignoring the robot base rotation and considering only links 1 and 2 and joints 1 and 2 ([A2], Section 3), of the robot shown in Fig. 10 of [2]. Therefore, "strictly speaking" our analytical SCARA Robot compliance model [A1] is perfectly valid, under these conditions, for the purpose of comparison only.

3. The "clarification" provided here is obvious. Force

measurements can be obtained by sensing other variables and carrying out the appropriate calibration.

Additional References

A1 ElMaraghy, H. A., and Johns, B., 1988, "An Investigation into the Compliance of SCARA Robots—Part 1: Analytical Model," ASME JOURNAL OF DYNAMIC SYSTEMS, MEASUREMENT, AND CONTROL, Vol. 110, 1988, pp. 18-22.

A2 ElMaraghy, H. A., and Johns, B., "An Investigation into the Compliance of SCARA Robots—Part II: Experimental and Numerical Validation," ASME JOURNAL OF DYNAMIC SYSTEMS, MEASUREMENT, AND CONTROL, Vol. 110, 1988, pp. 23-30.

A3 Bourrieres, J. P., Jeannier, P., and Lhote, F., "Intrinsic Compliance of Position-Controlled Robots-Applications in Assembly," 5th International Conference on Assembly Automation, 22-24 May, 1984, Paris, France, pp. 133-142.