Mechanical Design of a Modular Robot for Industrial Applications

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Abstract

Modular robots consist of standard units such as joints, links, and end effectors that can be efficiently configured into the most suitable manipulator geometry for a given (multi-operation) task. The fundamental difference between current (standard) industrial robots and modular robots lies on the design approach followed. Most of the current industrial robots have been designed as nonreconfigurable universal systems capable of performing a large number of tasks, though not under global optimal conditions. Modular robot inventories, on the other hand, are aimed at yielding a number of different robot geometries, where each one is configured to an optimal geometry for a specific task.

The objective of our ongoing research in the area of mechanical design of modular robots is to develop an inventory of basic modular units. We present some of our research results on the conceptual design of a modular robot inventory in this paper. The individual modular robot units that are presented include one degree-of-freedom (dof) main and end-effector joints (rotary and prismatic types), and a variety of links and adapters. These units are specifically designed for industrial applications. Some flexibility in terms of reconfigurability is sacrificed to achieve practical designs to answer the needs of the manufacturing industry.

***Keywords**: Robot Design, Flexible Automation, Robotic Manufacturing.*

Introduction

Most current industrial robots can be considered as universal solutions to a certain class of material handling problems. These systems usually possess software flexibility in terms of reprogrammability, and minimal mechanical hardware flexibility in terms of reconfigurability of the robot into a different manipulator-arm geometry. Therefore, the user selection of a robot geometry for a set of tasks at hand implies determining a universal manipulator arm capable of performing all desired tasks. This usually results in the underutilization of the robot. This problem can be alleviated by utilizing a modular robot that consists of an inventory of units from which different (optimal) robot geometries can be configured for different tasks at hand. Modularity in robotics can, therefore, be one of the keys to improved productivity and greater flexibility, providing the manufacturing industry with high utilization and optimal operation of robots.[1,2]

The four main research developments reported in the technical literature (other than the research conducted at the University of Toronto) are the LUT/Martonair Modular System at the Loughborough University of Technology,[3] the Modular Robot System at the University of Stuttgart,[4] the Reconfigurable Modular Manipulator System at the Carnegie Mellon University,[5] and the Structural Modules at the University of Texas.[1]

The modular robot in Reference 3 consists of pneumatic linear modules that are either end-stop or servo-controlled. The modular robot in Reference 4 consists of a variety of rotational joints actuated by AC motors in conjunction with differential gears and links of square cross section. The system in Reference 5 consists of roll and pitch type, one degree-of-freedom (dof) rotary joints actuated by DC motors in conjunction with harmonic-drive transmissions, and links of circular cross section. The modular robot structures presented in Reference 1 include one dof elbow, two dof knuckles, and three dof shoulders and wrists.

All of the aforementioned projects and the ongoing Modular Robot development project at the University of Toronto[6] aim to develop inventory components that can be reconfigured into a desired manipulator geometry. However, most of the suggested actuator units are too heavy to be of practical use for industrial tasks, mainly due to the unavailability of state-of-the-art, lightweight electric motors. In this paper, we present an inventory of modular robot units that include actuators based on the use of a remote-actuation technique similarly employed in current industrial robots. The use of these self-contained actuators, combined with the other units presented in this paper, can alleviate some of the weight problems encountered in the design of modular robots.

Modular Robot Inventory

The main design requirements for modular robot units that are adhered to by most research projects are as follows:

- Each unit should be self-contained and independent,
- Each unit should be connectable to any other unit, regardless of its type and size, and,
- Each unit should be designed for minimum weight and inertia.

An inventory of units satisfying these requirements would be capable of yielding a large number of different robot geometries. However, large-weight actuators within such an inventory would restrict the introduction and use of modular robots in the manufacturing industry in the near future. Robot geometries configured using these actuators could be severely restricted in their operation capabilities; namely, velocity, payload, accuracy, etc.

Careful examination of the mechanical configurations of current industrial robots would show that their heavy actuators are located around the base and use remote-actuation techniques to transmit power to distant joints. Modular robot designs previously reported in the technical literature do not employ this approach—mainly to maximize flexibility.

In this paper, an inventory of modular robot units that includes actuator designs based on the remote-actuation technique are presented. When compared to previous modular robot systems,[3-6] some flexibility might be lost using this design approach, in terms of having an inventory of units that can yield only a limited number of robot geometries. However, such a middle-of-the-way modular robot design can address current and near-future needs of the manufacturing industry, where production flexibility is still limited by a small number of frequent set-up changes due to product or model variations.

A modular robot system that can be efficiently reconfigured into a small number of different robot geometries and yield acceptable operation capabilities would be suitable in such an environment. An inventory of modular robot units that addresses this issue is presented in this section.

Connection of Units

All units included in the proposed inventory are joined using a standard four-bolt connection scheme between two circular flat surfaces (*Figure 1*). This scheme is preferred over a flange-connection scheme to reduce weight and yield compact connection.

The linear alignment of two units about their perpendicular common axis is based on the machining accuracy of the two connecting surfaces. The rotational alignment, on the other hand, is based on the machining accuracy of the step-type connections and through the use of an alignment pin (note the use of cross section A-A in all figures). The connection force and the torsional and bending stiffnesses are based on the normal forces achieved by the fastening of the four bolts.

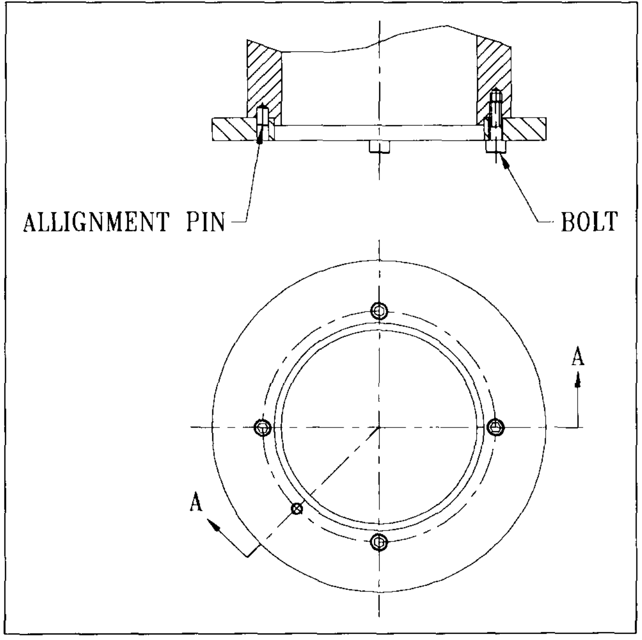

Figure 1
Connection Scheme

Links

In the context of this paper, links refer to units that provide the robot with the overall length it must achieve. In general, it can be assumed that the orientation of a link unit in a future arm geometry cannot be predefined relative to its cross section. Therefore, the direction in which the bending moment would be the largest cannot be foreseen at the design stage of the links. Consequently, to maintain design flexibility, the only natural choice for the cross section of the links would be a circular one. This has the additional advantage of being well suited for torsional loads. To comply with the third design requirement, a hollow cylindrical link geometry is proposed (*Figure 2*). The strength/weight and stiffness/weight ratios of a hollow cylinder are much higher than those of a full cylinder; although at the expense of a larger outer diameter.[7]

A special base link is also included in the proposed inventory to provide a stable, larger connection to an external platform *Figure 3*.

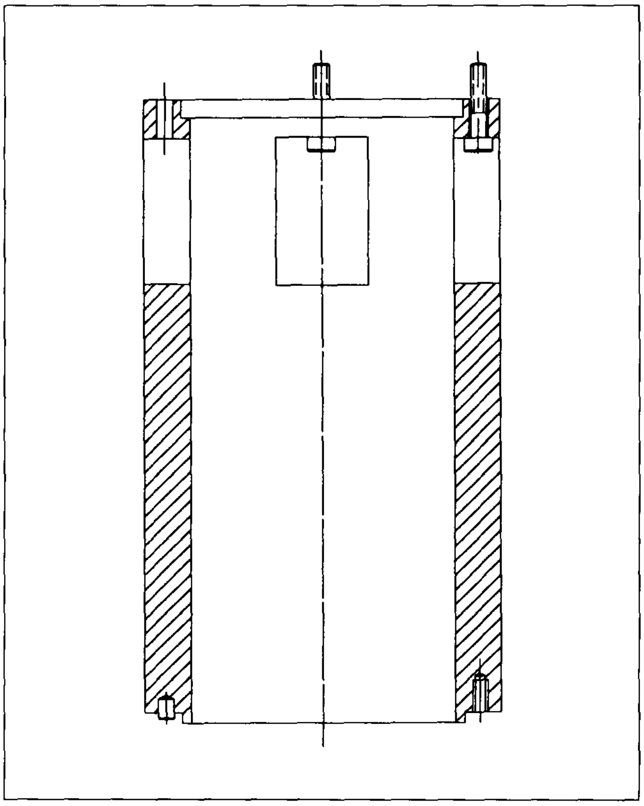

Figure 2
Link Design

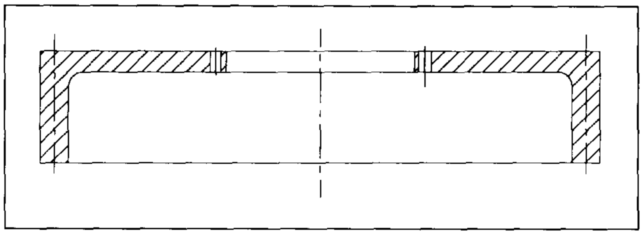

Figure 3
Base Design

Main Joints

The electric type actuator was chosen for the design of rotary and prismatic joints after a study of most available actuation techniques.[6] Transmission-incorporated actuators were conceptualized instead of direct-drive actuators, mainly due to weight considerations.[8] Two types of main (as opposed to end-effector type) rotary-joint actuators and one type of a prismatic-joint actuator were developed; namely, R-Actuator-M, R-Actuator/Link-M, and P-Actuator-M, respectively.

R-Actuator-M

The objective of this design is to provide a self-contained, compact rotary-axis actuator that can be used as a rotary joint. The actuator includes a DC motor, a harmonic-drive transmission, and an encoder (*Figure 4*). This actuator is intended for use near the base of the robot due to its heavy weight (proportional to its high torque-output capability). The harmonic-drive transmission is proposed as a suitable choice for the transmission of power.[7]

Since two actuators might have to be assembled in a sequence with perpendicular rotational axes, an intermediary lightweight, shell-type adapter, Adapter-1, is proposed (*Figure 4*).

R-Actuator/Link-M

The objective of this design is to provide actuation to remote joints. The self-contained unit shown in *Figure 5* consists of a standard rotary actuator coupled to an additional transmission unit for remotely transmitting power to the joint-end of the unit. The unit, as shown in *Figure 5*, is a telescopic variable-length type. In order to set it to a specific length, the joint-end is completely withdrawn and the encoder is set to zero. The actuator is then activated to displace the joint-end for a specific number of encoder counts corresponding to the

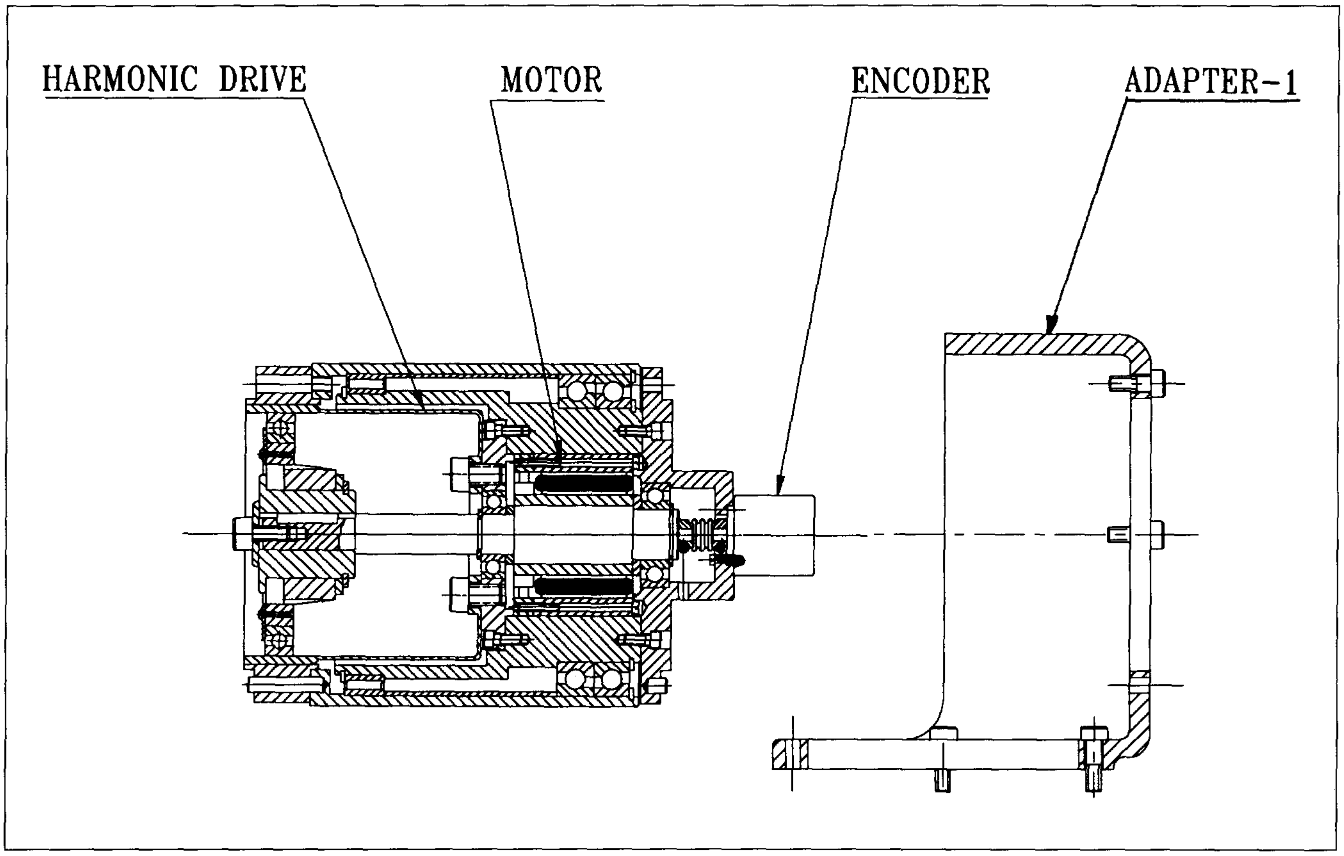

Figure 4
R-Actuator-M Design

desired extension. Once this is accomplished, the three bolts are tightly fastened to prevent slippage between the two contact surfaces of the telescopic unit during the operation of the robot.

The R-Actuator/Link-M can be thought of as two units combined into one; namely, a rotary actuator providing power to a remote joint, and a variable-length link. Note that the shaft used in the additional transmission unit can be replaced by a shorter or longer one according to the length of the actuator unit. An additional bushing is designed for insertion at the joint-end of the unit to preserve the standard connection scheme between the R-Actuator/Link-M and other units (*Figure 5*).

P-Actuator-M

The objective of this design is to provide a self-contained compact linear-axis actuator that can be used as a prismatic joint. The design is of telescopic type and includes a DC motor, leadscrew transmission, and encoder (*Figure 6*).

End Effector Joints

Two types of rotary-joint actuators and a prismatic-joint actuator were considered to form an inventory of end effector joints. A three-dof end effector capable of performing yaw, pitch, and roll motions is shown in *Figure 7*. The two small actuators, R-Actuator-E, are conceptually the same design as the main actuators shown in *Figure 4*, though with smaller DC motors and transmissions.

The second type of actuator unit shown in *Figure 7*, R-Actuator/Link-E, is based on the remote actuation principle. Its configuration is different than the main R-Actuator/Link-M unit shown in *Figure 5* to achieve compactness. The variability in the length of this unit is achieved through the use of precise locator holes drilled in its shell. A locator pin on a special interface adapter, Adapter-2, connects the R-Actuator/Link-E to the other (main) units and defines the length of the unit by fitting into one of these holes. The bolt provides the necessary connection strength (*Figure 8*). The second adapter

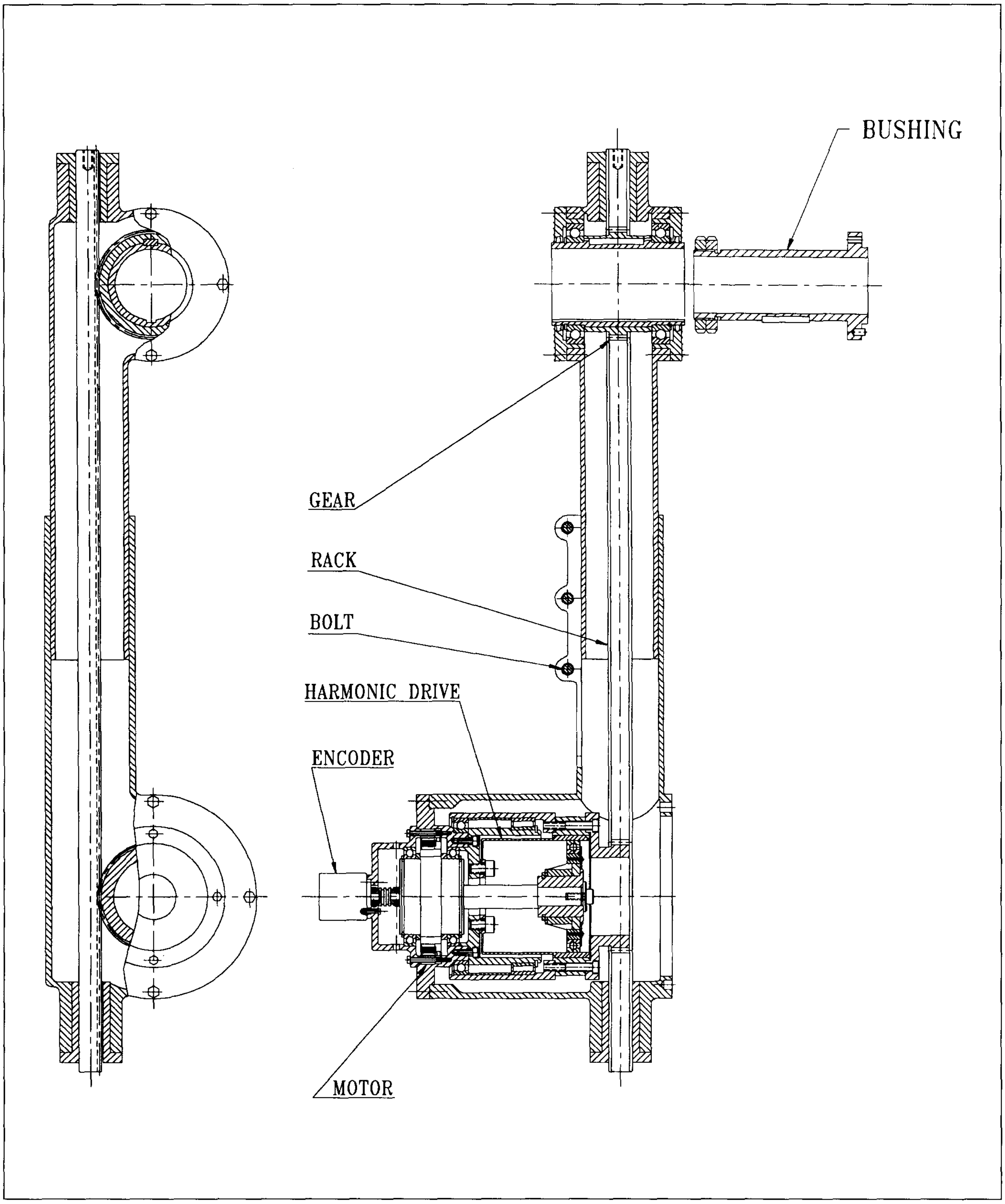

Figure 5
R-Actuator/Link-M Design

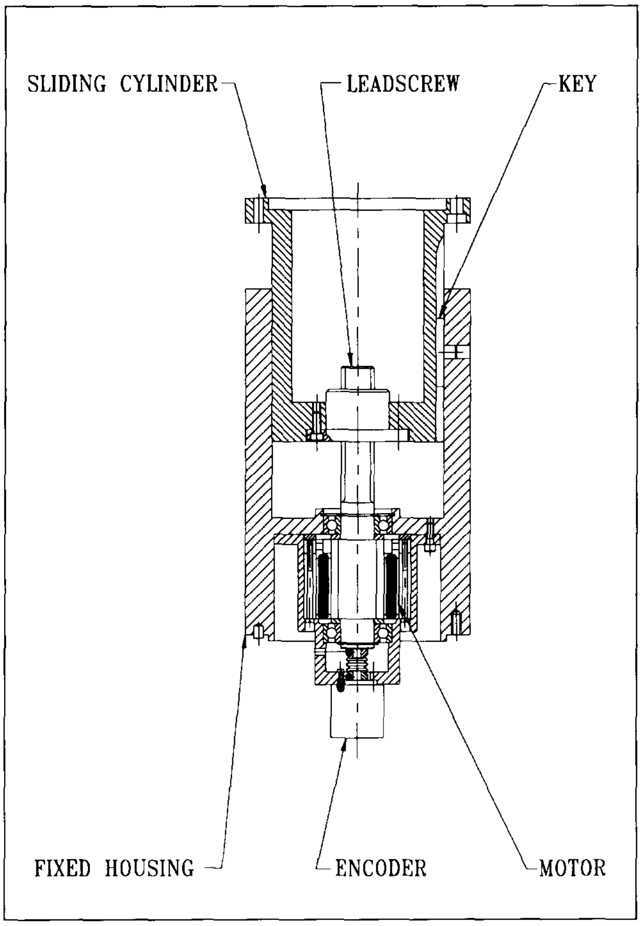

Figure 6
P-Actuator-M Design

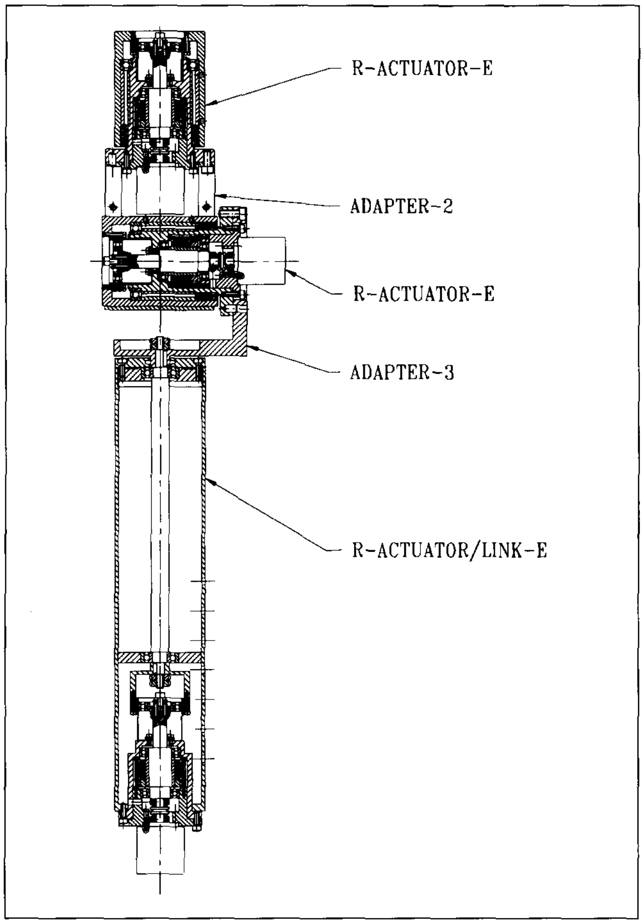

Figure 7
Three-dof End Effector Design

shown in *Figure 7*, Adapter-3, is a compact, light version of Adapter-1 shown in *Figure 4*. It connects two end-effector actuators in a sequence with perpendicular rotation axes.

The two-dof end effector shown in *Figure 9* consists of a rotary actuator, R-Actuator/Link-E; prismatic actuator, P-Actuator-E; and a special gear-box. The primary objective of the gear-box is to provide power to a remote joint with a rotation axis perpendicular to the rotation axis of the R-Actuator/Link-E unit. This arrangement has compactness and weight advantages over the main R-Actuator/Link-M unit design. However, it increases the size of the inventory by one more unit; namely, the gear box. The use of this two-dof end effector will be illustrated in the next section in the configuration of a Scara type robot.

Detailed drawings of the two-dof and three-dof end effectors are given in the Appendix.

An Example Modular-Robot Inventory

Modular robots are suitable for use in manufacturing environments where multiple robot geometries are needed to satisfy a set of tasks at hand (for optimal operating conditions). They would be employed as one robot geometry at a time for each task, where efficient setup changes would occur between the tasks to reconfigure the robot for the next task. The design problem for such a modular robot inventory can be defined as determining a set of modular robot units that would yield a set of optimal robot geometries corresponding to a set of desired tasks. This problem is an involved procedure and cannot be fully addressed in this paper.

This section illustrates that the modular robot units presented in the previous section can be utilized to yield a variety of robot geometries with different numbers of dof. The exemplary Articulated and Scara type robot geometries were selected for this illustration due to their popular use in the manufacturing industry (*Figures 10* and *11*). Note, however, that these geometries were not configured with respect to a set of tasks, but to show the use of modular units in configuring industrial robots. The individual modular units used in the two robots and the common inventory that includes these units are given in *Table 1*.

The savings in configuring two robots from a common inventory as opposed to buying two individual stand-alone robots is substantial—as can be deduced by comparing the last two columns in *Table 1*. However, the savings would be even greater if the same inventory would be used to configure additional robot geometries by simply adding extra modular robot units to the already existing inventory.

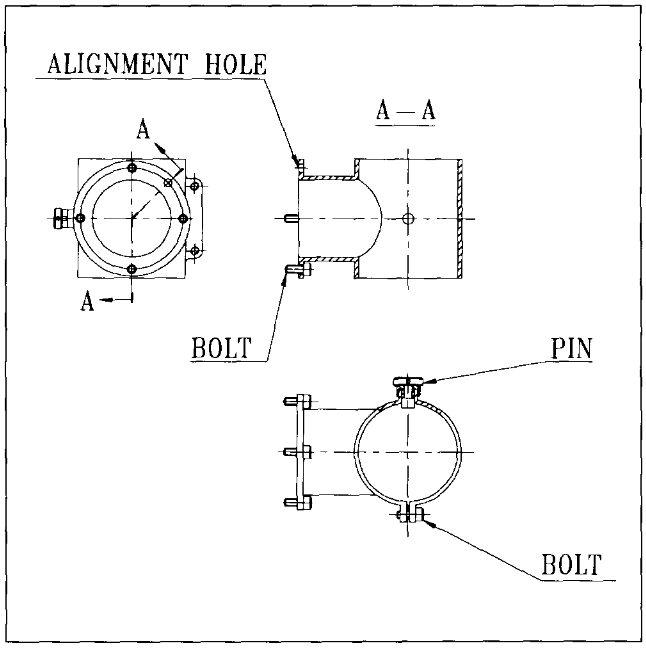

Figure 8
Adapter-2 Design

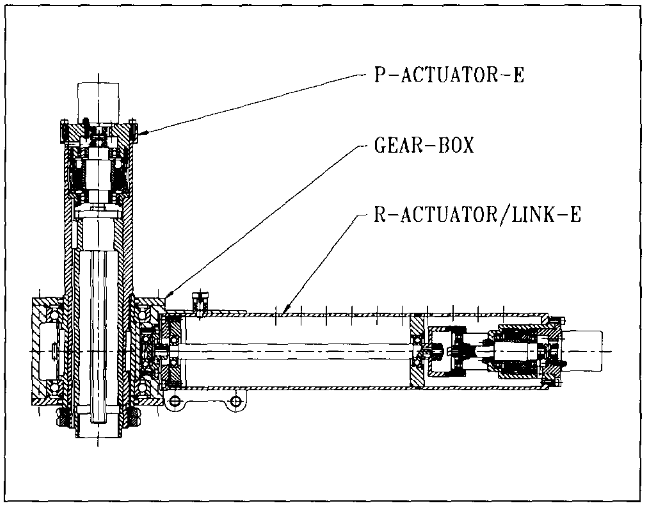

Figure 9
Two-dof End Effector Design

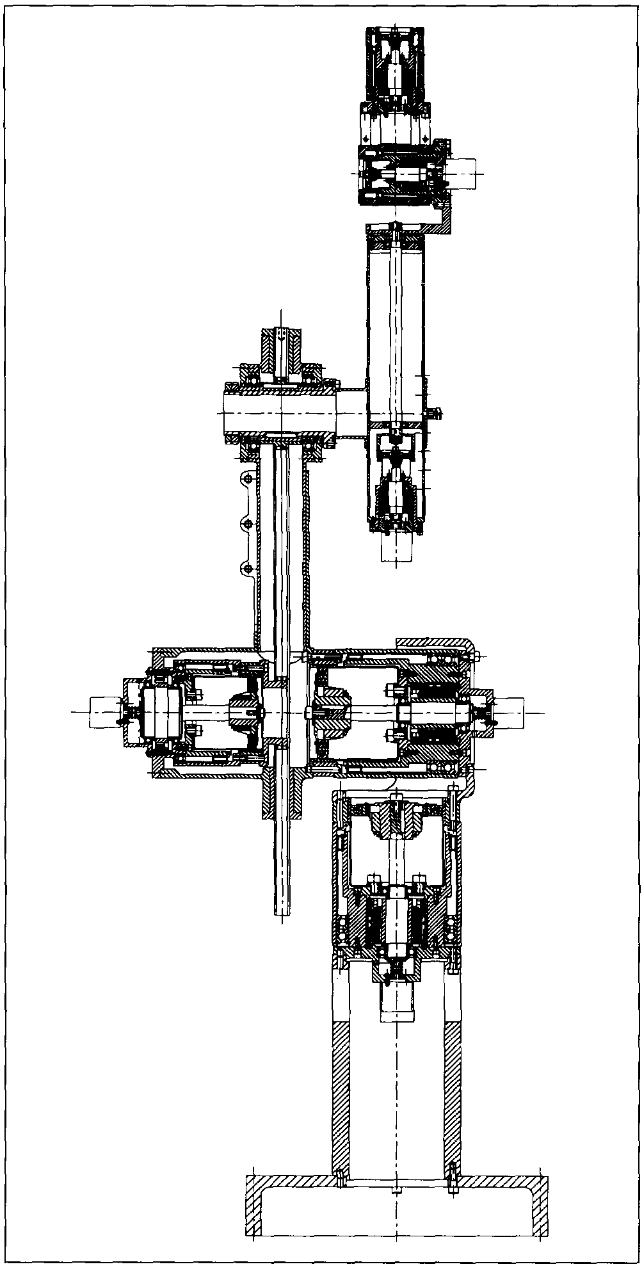

Figure 10
An Articulated Type Modular Robot Design

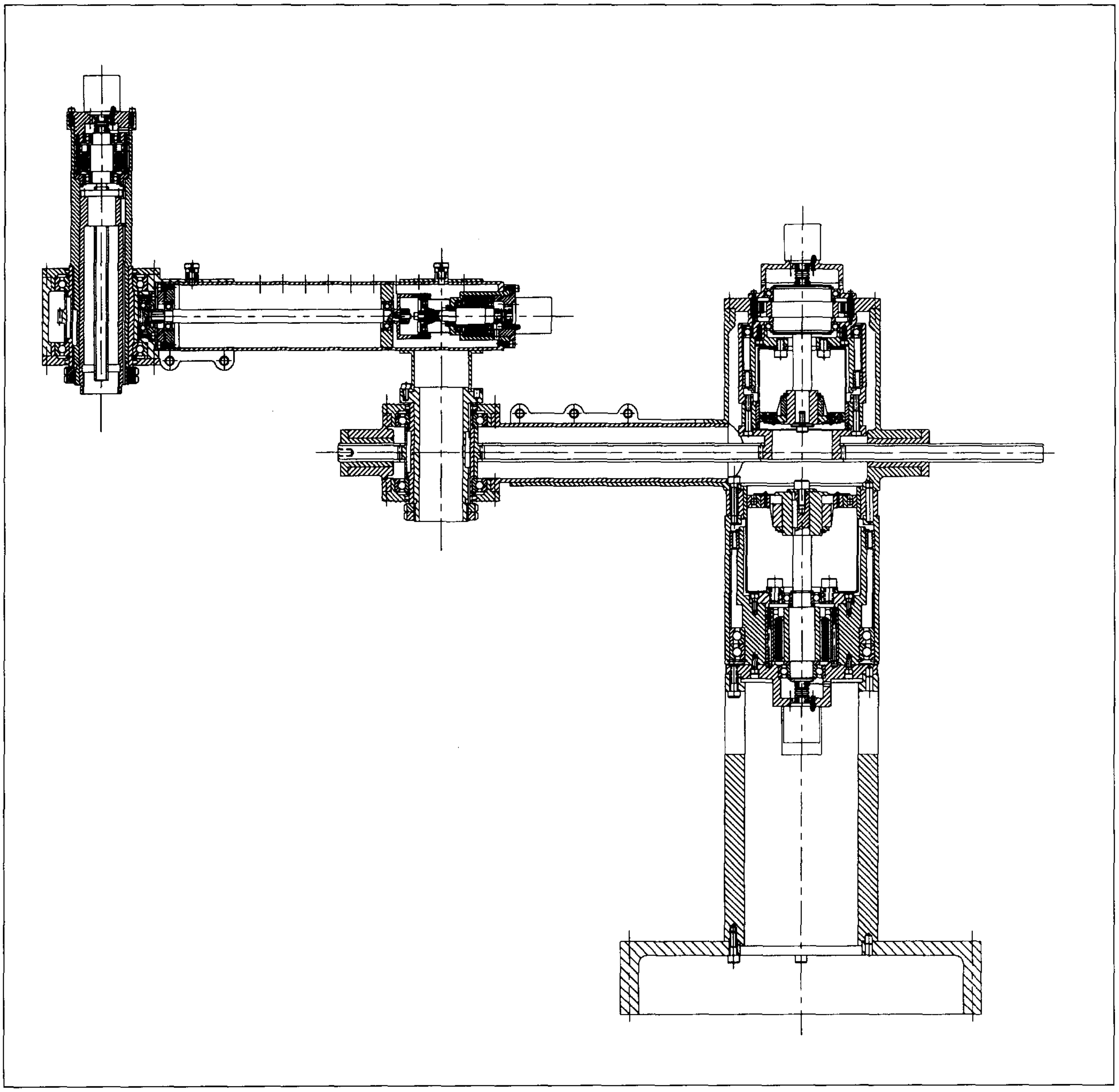

Figure 11
A Scara Type Modular Robot Design

Detailed drawings of the Articulated and the Scara robots are given in the Appendix.

Conclusions

This paper presents the conceptual mechanical design of a modular robot. The design approach followed herein is distinguishable from other modular robot design approaches presented in the literature in terms of its adaptability to the current and near-future needs of the manufacturing industry. The individual units that were presented include one degree-of-freedom (dof) main and effector joints (rotary and prismatic), and a variety of links/adapters. The unique design of some of the actuators allows remote actuation of distant joints; there-

Table 1
Modular Robot Units.

Units	Articulated Robot	Scara Robot	Common Inventory	(Total # of Units)
Base	1	1	1	(2)
Link	1	1	1	(2)
R-Actuator-M	2	1	2	(3)
R-Actuator/Link-M	1	1	1	(2)
R-Actuator-E	2	-	2	(2)
R-Actuator/Link-E	1	1	1	(2)
P-Actuator-E	-	1	1	(1)
Gear-Box	-	1	1	(1)
Adapter-1	1	-	1	(2)
Adapter-2	1	1	1	(2)
Adapter-3	1	-	1	(1)
Bushing	1	1	1	(2)

fore, heavy components are located closer to the base of the robot. Although only two robot geometries were configured and illustrated in this paper, other robot configurations with different geometries and dof can be obtained utilizing the proposed inventory of modular robot units. The selection of specific materials, motors, transmissions, etc. was addressed in this paper since such a selection is task dependent. Thus, the performance characteristics of a modular robot configured from modules must be carefully analyzed prior to its manufacture.

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Appendix: Detailed Drawings

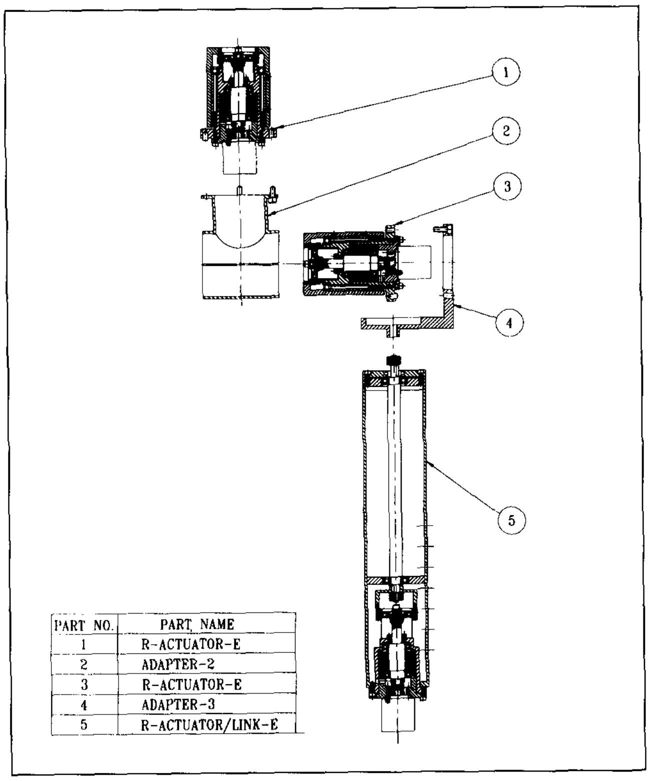


Figure A1
Exploded-Assembly View of the Three-dof End Effector Design

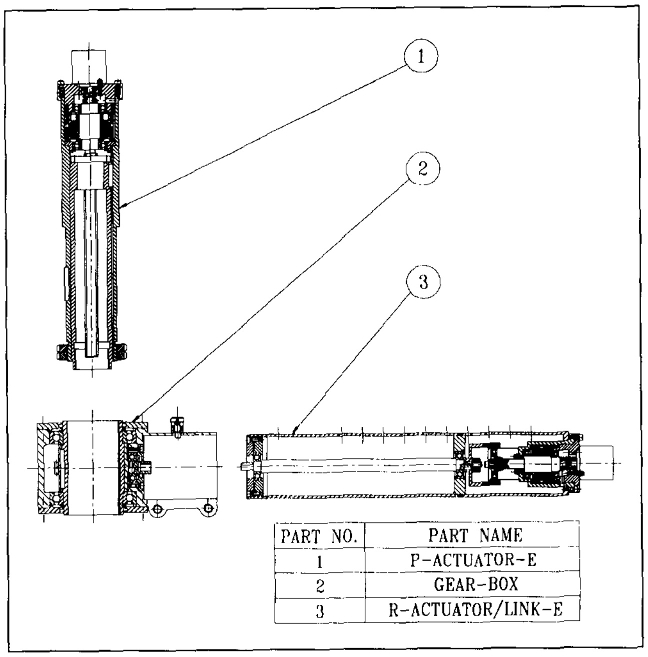
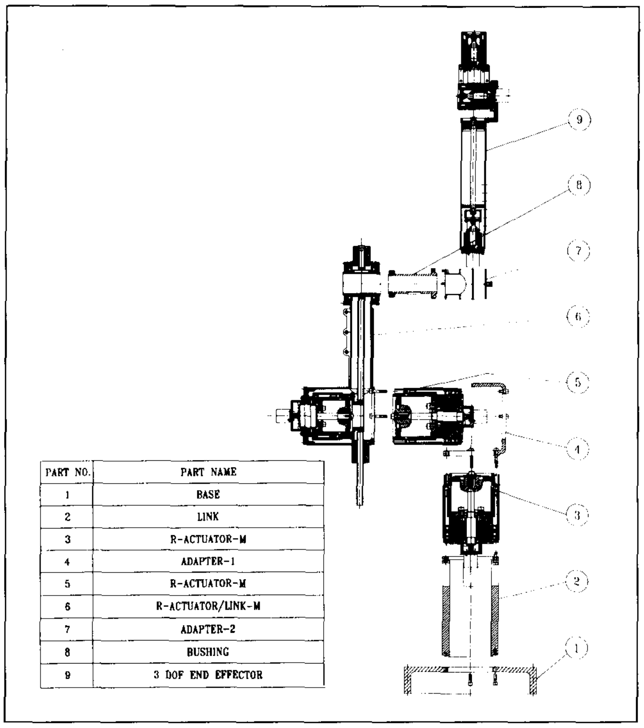
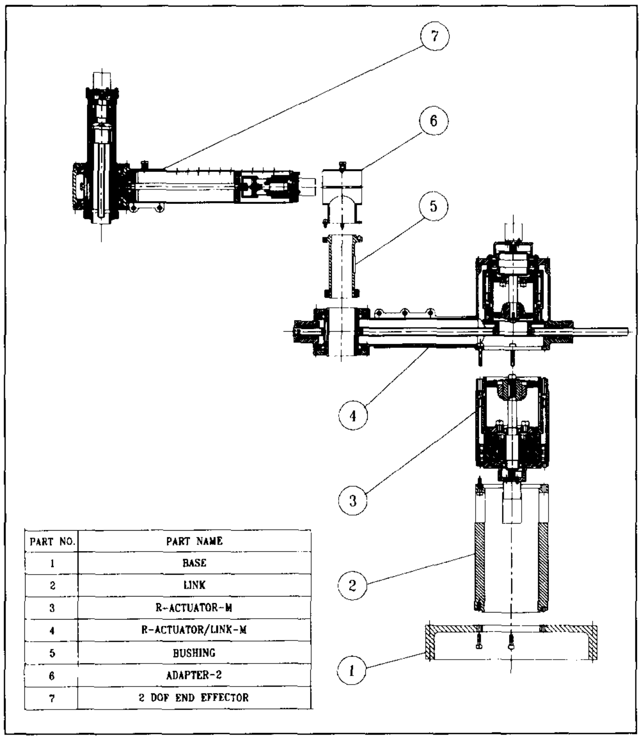


Figure A2
Exploded-Assembly View of the Two-dof End Effector Design



PART NO.	PART NAME
1	BASE
2	LINK
3	R-ACTUATOR-M
4	ADAPTER-1
5	R-ACTUATOR-M
6	R-ACTUATOR/LINK-M
7	ADAPTER-2
8	BUSHING
9	3 DOF END EFFECTOR

Figure A3
Exploded-Assembly View of the Articulated Type Modular Robot Design



PART NO.	PART NAME
1	BASE
2	LINK
3	R-ACTUATOR-M
4	R-ACTUATOR/LINK-M
5	BUSHING
6	ADAPTER-2
7	2 DOF END EFFECTOR

Figure A4
Exploded-Assembly View of the Scara Type Modular Robot Design

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