CHAPTER 2
ROBOT MECHANISMS

The programmability of the industrial robot using computer software makes it both flexible in the way it works and versatile in the range of tasks it can accomplish. The most generally accepted definition of a *robot* is a reprogrammable, multifunction manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions to perform a variety of tasks. Robots can be floor-standing, benchtop, or mobile.

Robots are classified in ways that relate to the characteristics of their control systems, manipulator or arm geometry, and modes of operation. There is no common agreement on or standardizations of these designations in the literature or among robot specialists around the world.

A basic robot classification relates to overall performance and distinguishes between limited and unlimited sequence control. Four classes are generally recognized: limited sequence and three forms of unlimited sequence—point-to-point, continuous path, and controlled path. These designations refer to the path taken by the end effector, or tool, at the end of the robot arm as it moves between operations.

Another classification related to control is *nonservoed* versus *servoed*. Nonservoed implies open-loop control, or no closed-loop feedback, in the system. By contrast, servoed means that some form of closed-loop feedback is used in the system, typically based on sensing velocity, position, or both. Limited sequence also implies nonservoed control while unlimited sequence can be achieved with point-to-point, continuous-path, or controlled-path modes of operation.

Robots are powered by electric, hydraulic, or pneumatic motors or actuators. Electric motor power is most popular for the major axes of floor-standing industrial robots today. Hydraulic-drive robots are generally assigned to heavy-duty lifting applications. Some electric and hydraulic robots are equipped with pneumatic-controlled tools or end effectors.

The number of degrees of freedom is equal to the number of axes of a robot, and is an important indicator of its capability. Limited-sequence robots typically have only two or three degrees of freedom, but point-to-point, continuous-path, and controlled-path robots typically have five or six. Two or three of those may be in the wrist or end effector.

Most heavy-duty industrial robots are floor-standing. Figure 1 shows a typical floor-standing robot system whose principal axes are powered by responsive electric motors. Others in the same size range are powered by hydraulic motors. The console contains a digital computer that has been programmed with an operating system and applications software so that it can perform the tasks assigned to it. Some robot systems also include training pendants—handheld pushbutton panels connected by cable to the console that permit direct control of the robot.

The operator or programmer can control the movements of the robot arm or manipulator with pushbuttons or other data input devices so that it is run manually through its complete task

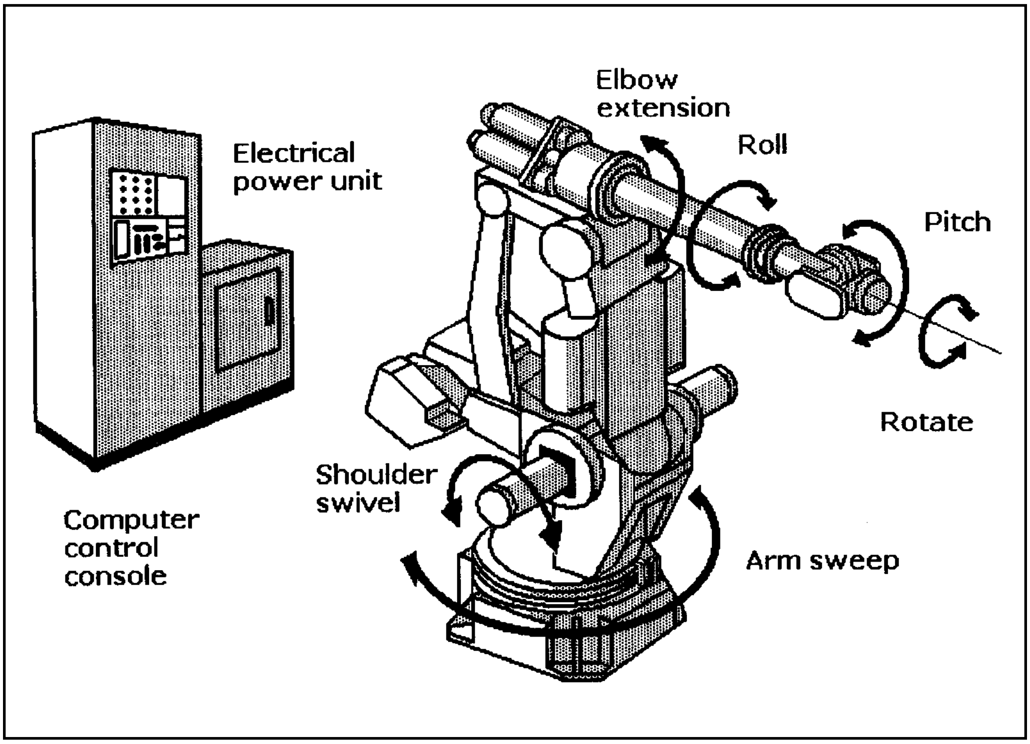


Fig. 1 Components of a floor-standing, six-degree-of-freedom industrial robot. The principal axes are driven by servo-controlled electric motors. The digital computer and remote-control pendant are located in the computer control console.

sequence to program it. At this time adjustments can be made to prevent any part of the robot from colliding with nearby objects.

There are also many different kinds of light-duty assembly or pick-and-place robots that can be located on a bench. Some of these are programmed with electromechanical relays, and others are programmed by setting mechanical stops on pneumatic motors.

Robot versus Telecheric

The true robot should be distinguished from the manually controlled manipulator or *telecheric*, which is remotely controlled by human operators and not programmed to operate automatically and unattended. These machines are mistakenly called robots because some look like robots or are equipped with similar components. Telecherics are usually controlled from a remote location by signals sent over cable or radio link.

Typical examples of telecherics are manually controlled manipulators used in laboratories for assembling products that contain radioactive materials or for mixing or analyzing radioactive materials. The operator is shielded from radiation or hazardous fumes by protective walls, airlocks, special windows, or a combination of these. Closed-circuit television permits the operator to view the workplace so that precise or sensitive work can be performed. Telecherics are also fitted to deep-diving submersibles or extraterrestrial landing platforms for gathering specimens in hostile or inaccessible environments.

Telecherics can be mobile machines equipped with tanklike treads that can propel it over rough terrain and with an arm that can move in three or more degrees of freedom. Depending on its mission, this kind of vehicle can be equipped with handlike grippers or other specialized tools for performing various tasks in environments where hazardous materials have been spilled or where fires are burning. Other missions might include bomb disposal, firefighting, or gathering information on armed criminals or persons trapped in confined spaces following earthquakes or explosions. Again, a TV camera gives the operator information for guidance.

Robot Advantages

The industrial robot can be programmed to perform a wider range of tasks than dedicated automatic machines, even those that can accept a wide selection of different tools. However, the full benefits of a robot can be realized only if it is properly integrated with the other machines human operators, and processes. It must be evaluated in terms of cost-effectiveness of the performance or arduous, repetitious, or dangerous tasks, particularly in hostile environments. These might include high temperatures, high humidity, the presence of noxious or toxic fumes, and proximity to molten metals, welding arcs, flames, or high-voltage sources.

The modern industrial robot is the product of developments made in many different engineering and scientific disciplines, with an emphasis on mechanical, electrical, and electronic technology as well as computer science. Other technical specialties that have contributed to robot development include servomechanisms, hydraulics, and machine design. The latest and most advanced industrial robots include dedicated digital computers.

The largest number of robots in the world are limited-sequence machines, but the trend has been toward the electric-motor powered, servo-controlled robots that typically are floor-standing machines. Those robots have proved to be the most cost-effective because they are the most versatile.

Trends in Robots

There is evidence that the worldwide demand for robots has yet to reach the numbers predicted by industrial experts and visionaries some ten years ago. The early industrial robots were expensive and temperamental, and they required a lot of maintenance. Moreover, the software was frequently inadequate for the assigned tasks, and many robots were ill-suited to the tasks assigned them.

Many early industrial customers in the 1970s and 1980s were disappointed because their expectations had been unrealistic; they had underestimated the costs involved in operator training, the preparation of applications software, and the integration of the robots with other machines and processes in the workplace.

By the late 1980s, the decline in orders for robots drove most American companies producing them to go out of business, leaving only a few small, generally unrecognized manufacturers. Such industrial giants as General Motors, Cincinnati Milacron, General Electric, International Business Machines, and Westinghouse entered and left the field. However, the Japanese electrical equipment manufacturer Fanuc Robotics North America and the Swedish-Swiss corporation Asea Brown Boveri (ABB) remain active in the U.S. robotics market today.

However, sales are now booming for less expensive robots that are stronger, faster, and smarter than their predecessors. Industrial robots are now spot-welding car bodies, installing windshields, and doing spray painting on automobile assembly lines. They also place and remove parts from annealing furnaces and punch presses, and they assemble and test electrical and mechanical products. Benchtop robots pick and place electronic components on circuit boards in electronics plants, while mobile robots on tracks store and retrieve merchandise in warehouses.

The dire predictions that robots would replace workers in record numbers have never been realized. It turns out that the most cost-effective robots are those that have replaced human beings in dangerous, monotonous, or strenuous tasks that humans do not want to do. These activities frequently take place in spaces that are poorly ventilated, poorly lighted, or filled with noxious or toxic fumes. They might also take place in areas with high relative humidity or temperatures that are either excessively hot or cold. Such places would include mines, foundries, chemical processing plants, or paint-spray facilities.

Management in factories where robots were purchased and installed for the first time gave many reasons why they did this despite the disappointments of the past ten years. The most frequent reasons were the decreasing cost of powerful computers as well as the simplification of both the controls and methods for programming the computers. This has been due, in large measure, to the declining costs of more powerful microprocessors, solid-state and disk memory, and applications software.

However, overall system costs have not declined, and there have been no significant changes in the mechanical design of industrial robots during the industrial robot's ten-year "learning curve" and maturation period.

The shakeout of American robot manufacturers has led to the near domination of the world market for robots by the Japanese manufacturers who have been in the market for most of the past ten years. However, this has led to de facto standardization in robot geometry and philosophy along the lines established by the Japanese manufacturers. Nevertheless, robots are still available in the same configurations that were available five to ten years ago, and there have been few changes in the design of the end-use tools that mount on the robot's "hand" for the performance of specific tasks (e.g., parts handling, welding, painting).

Robot Characteristics

Load-handling capability is one of the most important factors in a robot purchasing decision. Some can now handle payloads of as much as 200 pounds. However, most applications do not require the handling of parts that are as heavy as 200 pounds. High on the list of other requirements are "stiffness"—the ability of the robot to perform the task without flexing or shifting; accuracy—the ability to perform repetitive tasks without deviating from the programmed dimensional tolerances; and high rates of acceleration and deceleration.

The size of the manipulator or arm influences accessibility to the assigned floor space. Movement is a key consideration in choosing a robot. The robot must be able to reach all the parts or tools needed for its application. Thus the robot's working range or envelope is a critical factor in determining robot size.

Most versatile robots are capable of moving in at least five degrees of freedom, which means they have five axes. Although most tasks suitable for robots today can be performed by robots with at least five axes, robots with six axes (or degrees of freedom) are quite common. Rotary base movement and both radial and vertical arm movement are universal. Rotary wrist movement and wrist bend are also widely available. These movements have been designated as roll and pitch by some robot manufacturers. Wrist yaw is another available degree of freedom.

More degrees of freedom or axes can be added externally by installing parts-handling equipment or mounting the robot on tracks or rails so that it can move from place to place. To be most effective, all axes should be servo-driven and controlled by the robot's computer system.

Principal Robot Categories

There are four principal geometries for robot manipulators: (1) articulated, revolute, or jointed-arm (Figs. 2 and 3); (2) polar coordinate (Fig. 4); (3) Cartesian (Fig. 5); and (4) cylindrical (Fig. 6). However, there are many variations possible on these basic designs, including vertically jointed (Fig. 7), horizontally jointed, and gantry or overhead-configured.

The robot "wrist" is mounted on the end of the robot's arm and serves as a tool holder. It can also provide additional axes or degrees of freedom, which is particularly desirable when the end effector, such as welding electrodes or a paint spray gun, must be maneuvered within confined spaces. Three common forms of end effector are illustrated in Figs. 8, 9, and 10.

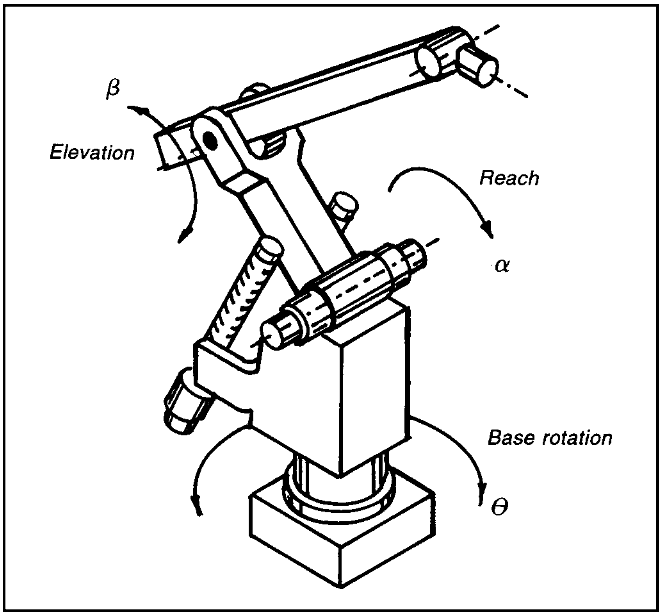


Fig. 2 A low-shoulder, articulated, revolute, or jointed-geometry robot has a base or waist, an upper arm extending from the shoulder to the elbow, and a forearm extending from the elbow to the wrist. This robot can rotate at the waist, and both upper and lower arms can move independently through angles in the vertical plane. The angle of rotation is θ (theta), the angle of elevation is β (beta), and the angle of forearm movement is α (alpha).

There are many different kind of end effectors, but among the most common are hand-like grippers that can pick up, move, and release objects. Some are general purpose, but others are specially machined to fit around specific objects. Crude in comparison with a human hand, the grippers must be able to pick up an object and hold it securely without damaging or dropping it. Three of the most common designs are illustrated in Figs. 11, 12, and 13.

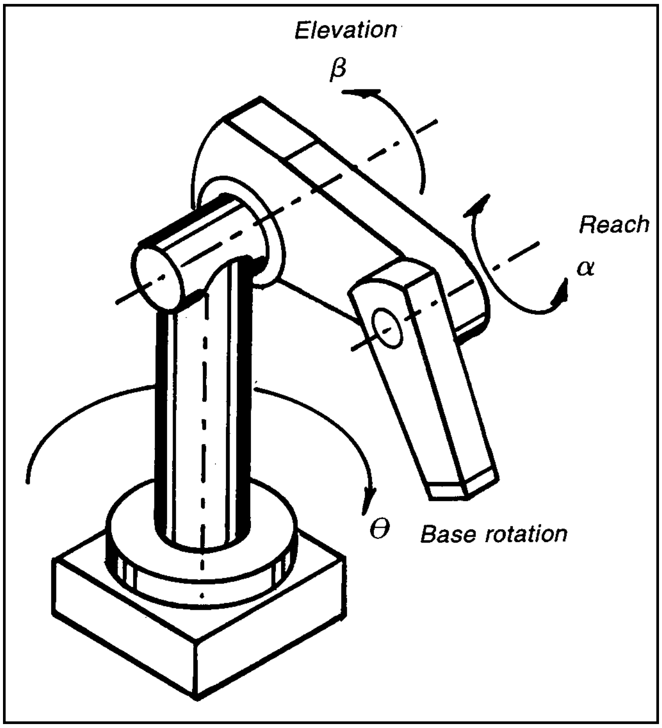


Fig. 3 A high-shoulder articulated, revolute, or jointed-geometry robot has a base or waist, an upper arm extending from the shoulder to the elbow, and a forearm extending from the elbow to the wrist. This robot can also rotate at the waist, and both upper and lower arms can move independently through angles in the vertical plane. As in Fig. 2, the angle of rotation is θ (theta), the angle of elevation is β (beta), and the angle of forearm movement is α (alpha).

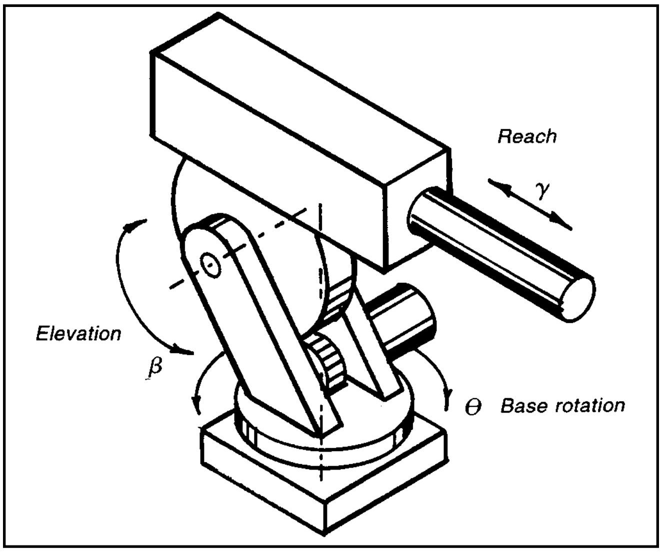


Fig. 4 A polar coordinate or gun-turret-geometry robot has a main body or waist that rotates while the arm can move in elevation like a gun barrel. The arm is also able to extend or reach. The angle of rotation in this robot is θ (theta), the angle of elevation is β (beta), and the reciprocal motion of the arm is γ (gamma).

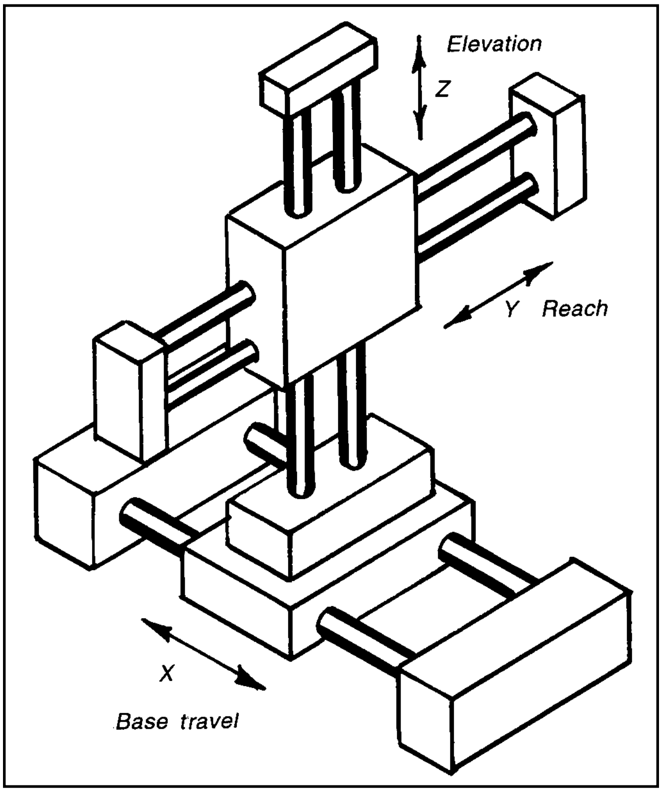


Fig. 5 The Cartesian-coordinate-geometry robot has three linear axes, X, Y, and Z. A moving arm mounted on a vertical post moves along a linear track. The base or X axis is usually the longest; the vertical axis is the Z axis; and the horizontal axis, mounted on the vertical posts, is the Y axis. This geometry is effective for high-speed, low-weight robots.

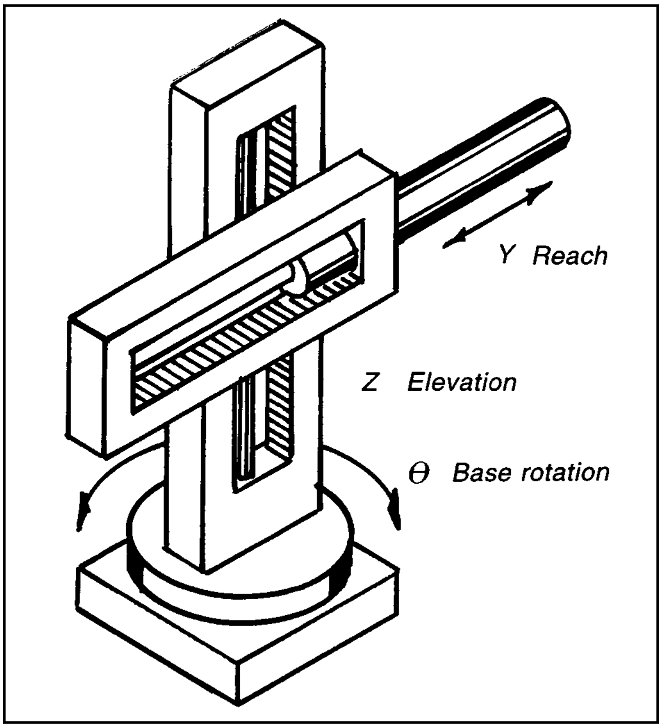


Fig. 6 The cylindrical-coordinate-geometry robot can have the same geometry as the Cartesian-coordinate robot (Fig. 5) except that its forearm is free to rotate. Alternatively, it can have a rotating waist like the polar-coordinate robot (Fig. 4) or the revolute-coordinate-geometry robot (Figs. 2 and 3). The Z axis defines vertical movement of the arm, and the Y axis defines traverse motion. Again, the angle of rotation is defined by θ (theta).

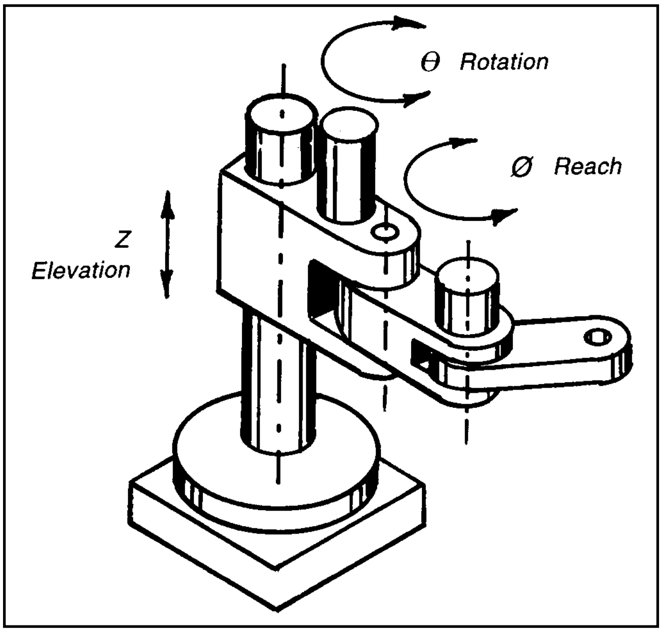


Fig. 7 A vertically-jointed robot is similar to an articulated robot, except that the mechanism is turned on its side, and the axes of rotation are vertical. The mechanism is then mounted on a vertical post or linear side, as shown. In another variation, the horizontally jointed robot, the mechanism is turned so that the slide is horizontal.

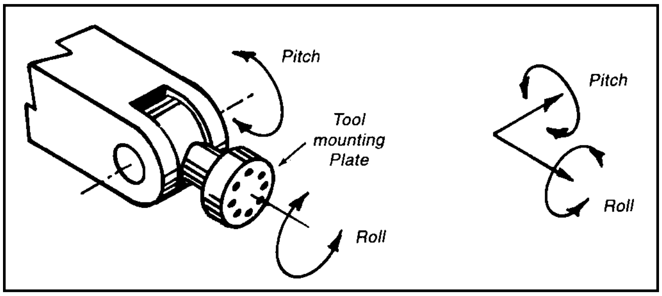


Fig. 8 A two-degree-of-freedom robot wrist can move a tool on its mounting plate around both pitch and roll axes.

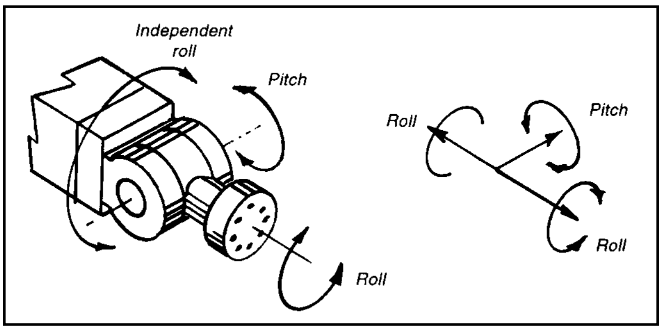


Fig. 9 This two-degree-of-freedom robot wrist can move a tool on its mounting plate around the pitch and two independent roll axes.

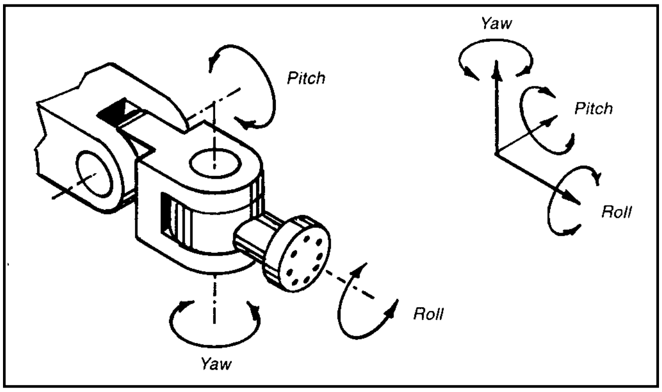


Fig. 10 A three-degree-of-freedom robot wrist can move a tool on its mounting plate around the pitch, roll, and yaw axes.

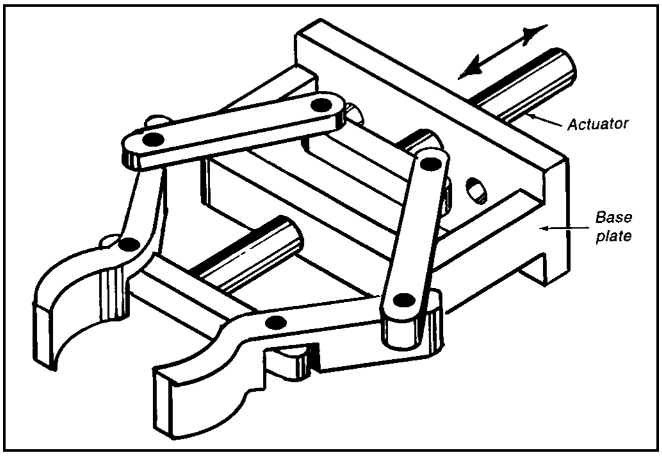


Fig. 11 A reciprocating lever mechanism opens and closes the jaws of this robot gripper, permitting it to grasp and release objects.

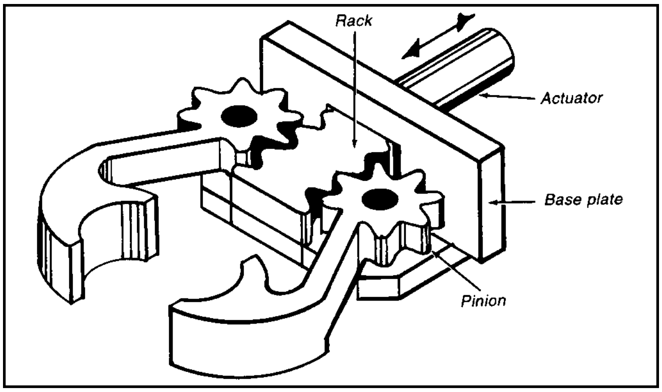


Fig. 12 A rack and pinion mechanism opens and closes the jaws of this robot gripper, permitting it to grasp and release objects.

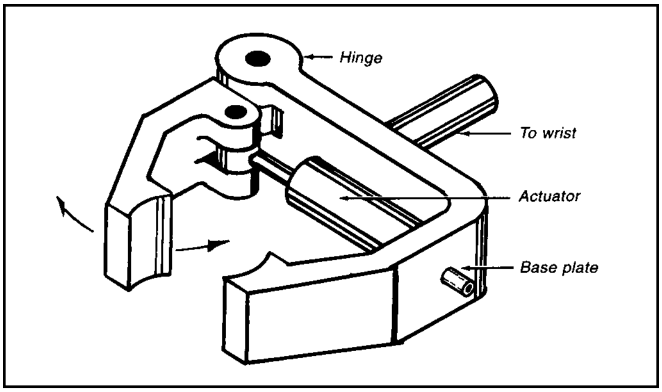


Fig. 13 A hydraulic or pneumatic piston opens and closes the jaws of this robot gripper, permitting it to grasp and release objects.

FANUC ROBOT SPECIFICATIONS

The data sheets for three robots from FANUC Robotics North America, Inc., Rochester Hills, Michigan, have been reproduced on the following pages to illustrate the range of capabilities of industrial robots now in production. These specifications include the manufacturer's ratings for the key characteristics: motion range and speed, wrist load moments and inertias, repeatability, reach, payload, and weight.

S-900*i*H/*i*L/*i*W Robots

There are three robots in the S-900*i* family: S-900*i*H, S-900*i*L, and S-900*i*W. They are floor-standing, 6-axis, heavy-duty robots with reaches of between 8 and 10 ft, (2.5 and 3.0 m) and maximum payloads of 441 to 880 lb (200 to 400 kg). S-900*i* robots can perform such tasks as materials handling and removal, loading and unloading machines, heavy-duty spot welding, and participation in casting operations.

These high-speed robots are controlled by FANUC R-J3 controllers, which provide point-to-point positioning and smooth controlled motion. S-900*i* robots have high-inertia wrists with large allowable moments that make them suitable for heavy-duty work in harsh environments. Their slim J3 outer arms and wrist profiles permit these robots to work in restricted space, and their small footprints and small i-size controllers conserve factory floor space. Many attachment points are provided on their wrists for process-specific tools, and axes J5 and J6 have precision gear drives. All process and application cables are routed through the arm, and there are brakes on all axes.

S-900*i* robots support standard I/O networks and have standard Ethernet ports. Process-specific software packages are available for various applications. Options include B-size controller cabinets, additional protection for harsh environments, a precision baseplate for quick robot exchanges, and integrated auxiliary axes packages.

S-500 Robot

The S-500 is a 6-axis robot with a reach of 9 ft (2.7 m) and a load capacity of 33 lb (15 kg). Equipped with high-speed electric servo-drives, the S-500 can perform a wide range of manufacturing and processing tasks such as materials handling, loading and unloading machines, welding, waterjet cutting, dispensing, and parts transfer.

The S-500 can be mounted upright, inverted, or on walls without modification, and it can operate in harsh uninhabited locations as well as on populated factory floors. Absolute serial encoders eliminate the need for calibration at power-up. Repeatability is ±0.010 in. (±0.25 mm), and axes 3 to 6 can reach speeds of 320°/s.

Features for increasing reliability include mechanical brakes on all axes and grease fittings on all lubrication points for quick and easy maintenance. RV speed reducers provide smooth motion at all speeds. Bearings and drives are sealed for protection, and cables are routed through hollow joints to eliminate snagging. Brushless AC servo motors minimize motor maintenance.

An optional drive for axis 6 is capable of speeds up to 600°/s. Other options include a 3.5-in. floppy-disk drive for storing data off-line and a printer for printing out data and programs. Also available are an RS-232C communication port and integrated auxiliary axes.

LR Mate 100*i* Robot

The LR Mate 100*i* is a 5-axis benchtop robot suitable for performing a wide range of tasks in environments ranging from clean rooms to harsh industrial sites. It has a nominal payload capacity of 6.6 to 8.8 lb (3 to 4 kg) and a 24.4-in. (620 mm) reach. Its payload can be increased to 11 lb with a shorter reach of 23.6 in. (600 mm) This modular electric servo-driven robot can perform such tasks as machine loading and unloading, materials handling and removal, testing and sampling, assembly, welding, dispensing, and parts cleaning.

The 100*i* robot can be mounted upright or inverted without modification, and its small footprint allows it to be mounted on machine tools. Repeatability is ±0.002 in. (±0.04 mm), and the axis 5 speed can reach 272°/s. Two integral double solenoid valves and the end effector connector are in the wrist. It is able to “double back” on itself for increased access, and axes 2 and 3 have fail-safe brakes. Standard software permits 3D palletizing and depalletizing of rows, columns, and layers simply by teaching the robot three points.

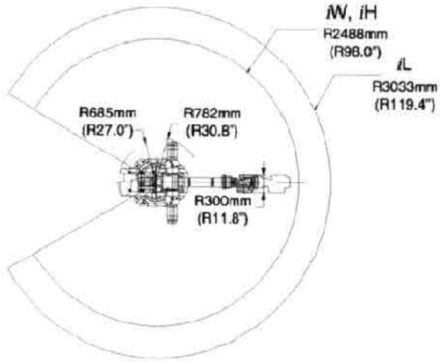
The FANUC R-J2 Mate *i*-Controller is easy to install, start up, troubleshoot, and maintain. The controller weighs approximately 110 lb (50 kg) and is housed in a small case measuring 14.9 in. wide by 18.5 in. high and 12.6 in. deep (380 × 470 × 320 mm). Its low-voltage I/O has 20 inputs (8 dedicated), 16 outputs (4 dedicated), and 4 inputs at the end-of-arm connector.

Reliability is increased and maintenance is reduced with brushless AC servo motors and harmonic drives on all axes. Only two types of motors are used to simplify servicing and reduce spare parts requirements. Bearings and drives are sealed for protection against harsh factory environments. There are grease fittings on all lubrication points for quick and easy maintenance, and easily removable service panels give fast access to the robot’s drive train. A standard IP65 dust and liquid intrusion package is included.

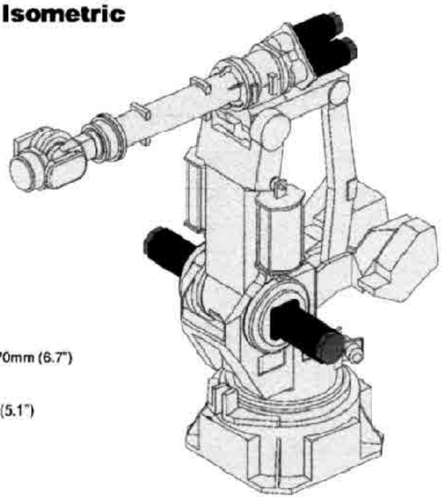
As options for the LR Mate 100*i*, Class 100 cleanroom and high-speed versions are offered. The cleanroom version can serve in biomedical research labs and high-precision production and testing facilities. A high-speed version with an axis 5 speed of 480°/s and a payload of 6.6 lb (3 kg) is available. Other options include additional integral valve packages, brakes for axis 1, and a higher-speed CPU to speed up path and cycle times. FANUC’s Sensor Interface serial communications software allows the robot to exchange data with third-party equipment such as bar code readers, vision systems, and personal computers, while its Data Transfer Function serial communications software allows two-way data exchange between the robot and a PC. This permits the robot to be controlled through a VB graphical interface.

S-900 *i*H/*i*L/*i*W Dimensions

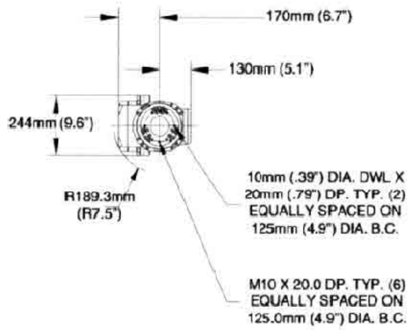
Top



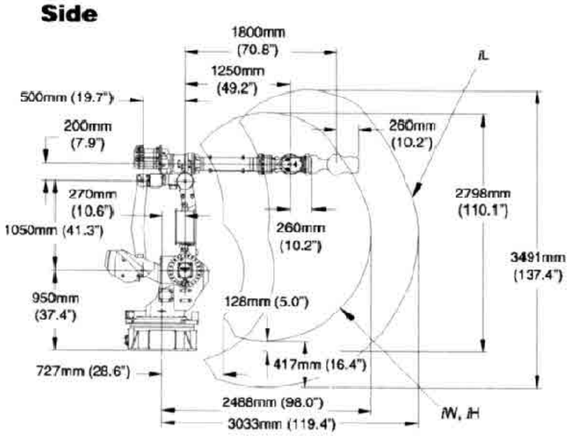
Isometric



Wrist ISO Flange



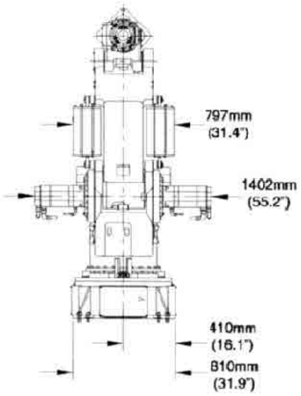
Side



S-900 *i*H/*i*L/*i*W Specifications

Items		S-900*i*H		S-900*i*L		S-900*i*W	
Motion range and speed	Axis 1	300°	120°/sec	300°	95°/sec	300°	95°/sec
	Axis 2	115°	120°/sec	115°	95°/sec	115°	95°/sec
	Axis 3	145°	125°/sec	145°	95°/sec	145°	95°/sec
	Axis 4	720°	115°/sec	720°	110°/sec	720°	100°/sec
	Axis 5	250°	115°/sec	250°	110°/sec	250°	100°/sec
	Axis 6	720°	200°/sec	720°	165°/sec	720°	160°/sec
Wrist load moments	Axis 4	120kg • m		130kg • m		140kg • m	
	Axis 5	120kg • m		130kg • m		140kg • m	
	Axis 6	65kg • m		70kg • m		70kg • m	
Wrist load inertias	Axis 4	1200kg • cm • sec^2		1200kg • cm • sec^2		1200kg • cm • sec^2	
	Axis 5	1200kg • cm • sec^2		1200kg • cm • sec^2		1200kg • cm • sec^2	
	Axis 6	300kg • cm • sec^2		600kg • cm • sec^2		600kg • cm • sec^2	
Reach		2488		3033		2488	
Max payload at J6		200kg (441 lbs)		220kg (484 lbs)		400kg (880 lbs)	
Mounting method		Floor		Floor		Floor	
Failsafe mech brakes		All axes		All axes		All axes	
Mech unit weight		1920kg (4230 lbs)		2030kg (4466 lbs)		1995kg (4395 lbs)	

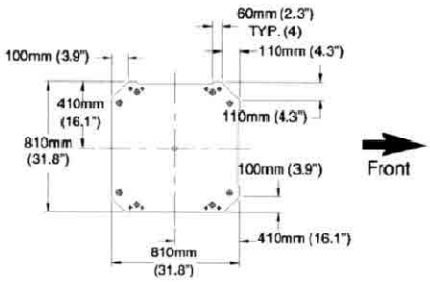
Front



FANUC Robotics

A New Age of Industry

Footprint



FANUC Robotics North America
3900 W. Hamlin Road
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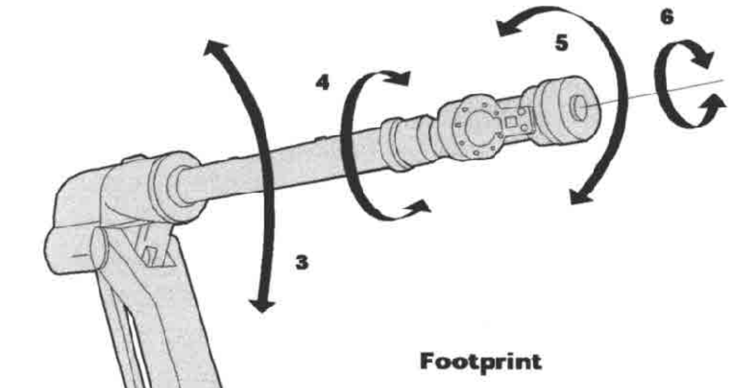
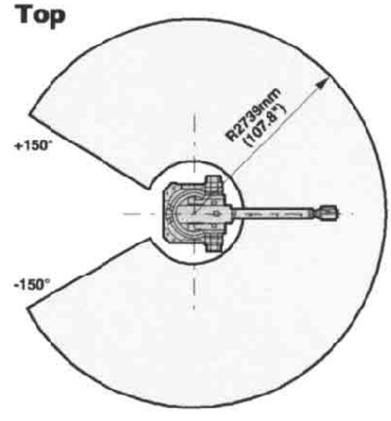
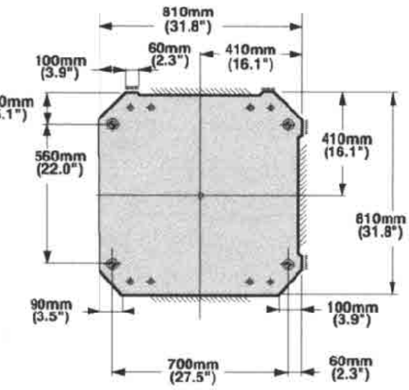
S-500 Dimensions



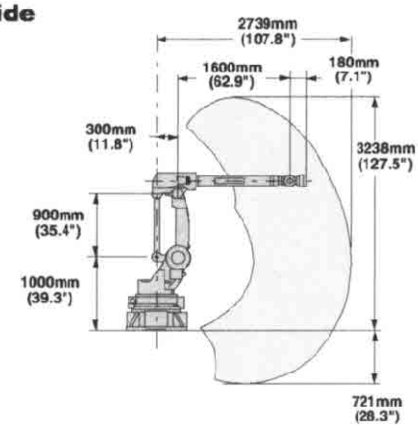
Top



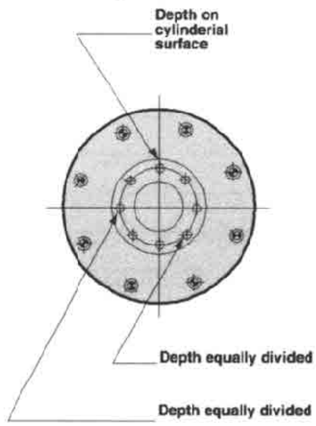
Footprint



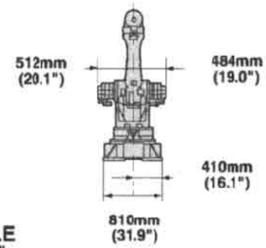
Side



Mounting Plate



Front



SCALE
1/100"

Items		Range	Speed
Motion range and speed	Axis 1	300°	90°/sec.
	Axis 2	160°	90°/sec.
	Axis 3	160°	320°/sec.
	Axis 4	480°	320°/sec.
	Axis 5	240°	320°/sec.
	Axis 6	900°	320°/sec.
	Axis 1	2.0 kgf • cm	
	Axis 2	3.0 kgf • cm	
	Axis 3	3.0 kgf • cm	
Load	Axis 1	2.2 kgf • cm • sec2	
	Axis 2	6.2 kgf • cm • sec2	
	Axis 3	6.2 kgf • cm • sec2	
		±0.25mm(±0.010")	
Max. load capacity		15kg (33 lbs)	
Mounting method			
Mechanical brakes		All axes	
Mechanical weight		900 kg (1985 lbs)	

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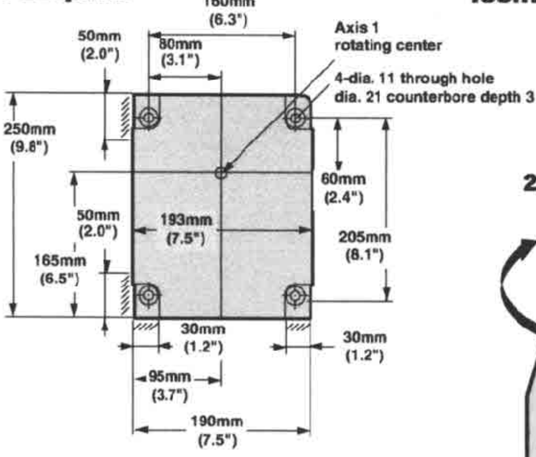
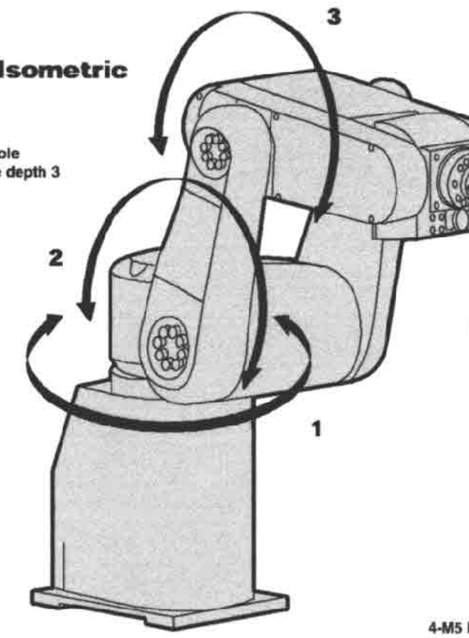
LR Mate 100*i* Dimensions

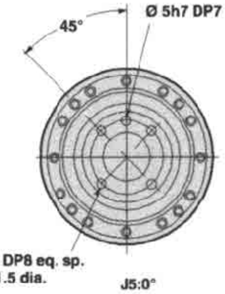
Footprint



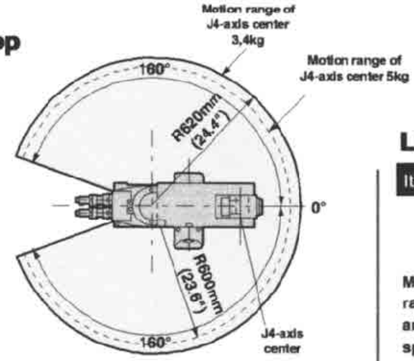
Isometric



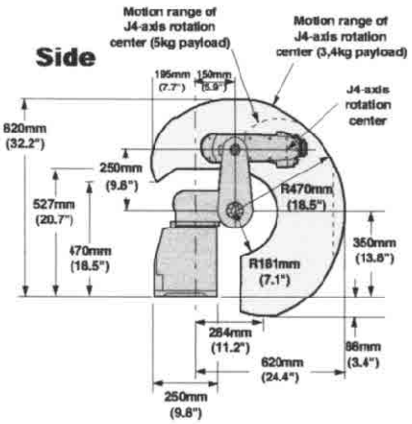
Mounting plate



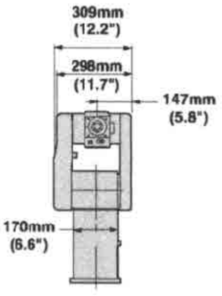
Top



Side



Front



SCALE
1/30"

LR Mate 100*i* Specifications

Items		3kg (6.6 lbs) payload			4kg (8.8 lbs) payload		5kg (11 lbs) payload	
		Standard & Cleanroom Versions		High Speed Version	Standard & Cleanroom Versions		Standard & Cleanroom Versions	
		Range	Speed	Speed	Range	Speed	Range	Speed
Motion range and speed	Axis 1	320°	180°/sec	240°/sec	320°	150°/sec	Same as 4kg (note 1)	
	Axis 2	185°	180°/sec	285°/sec	185°	150°/sec		
	Axis 3	365°	225°/sec	360°/sec	365°	180°/sec		
	Axis 4	240°	216°/sec	330°/sec	240°	100°/sec		
	Axis 5	400°	272°/sec	480°/sec	400°	250°/sec		
Moment	Axis 4	55.5 kgf • cm			74.0 kgf • cm		50.0 kgf • cm	
	Axis 5	40.0 kgf • cm			40.0 kgf • cm		4.4 kgf • cm (note 2)	
Load inertia	Axis 4	1.1 kgf • cm • s^2			1.4 kgf • cm • s^2		2.25 kgf • cm • s^2	
	Axis 5	0.41 kgf • cm • s^2			0.41 kgf • cm • s^2		0.51 kgf • cm • s^2	
Repeatability		±0.04mm (±0.002") based on JISB8432						
Mounting method		Upright/inverted						
Mechanical brakes		Axis 2, axis 3 (axis 1 option)						
Mechanical weight		32kg (70.5 lbs)						
Dust/water intrusion protection		Conforms to the IP65 standard for dust and liquid intrusion protection (seals may need periodic replacement if used with chlorine or gasoline based coolants)						
Notes		(1) In the case of 5kg wrist payload, the motion area and the wrist direction are limited (2) In the case of 5kg wrist payload, the wrist direction is limited to downward						

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MECHANISM FOR PLANAR MANIPULATION WITH SIMPLIFIED KINEMATICS

Simple combinations of actuator motions yield purely radial or purely tangential end-effector motions.

Goddard Space Flight Center, Greenbelt, Maryland

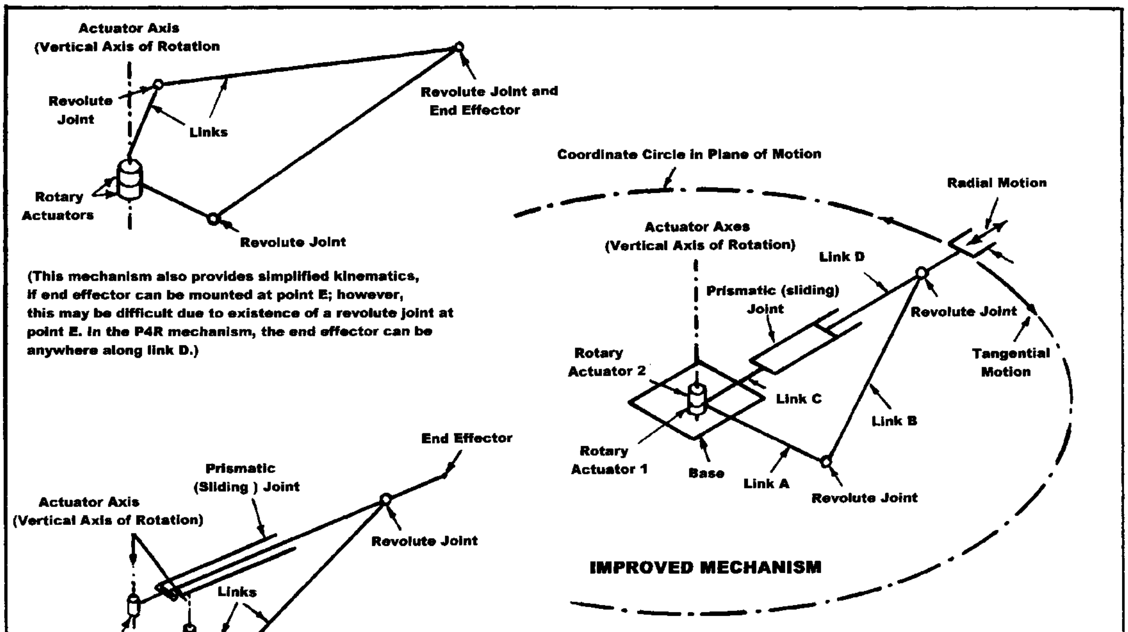
The figure schematically illustrates three manipulator mechanisms for positioning an end effector (a robot hand or other object) in a plane (which would ordinarily be horizontal). One of these is a newer, improved mechanism that includes two coaxial, base-mounted rotary actuators incorporated into a linkage that is classified as “P4R” in the discipline of kinematics of mechanisms because it includes one prismatic (P) joint and four revolute (R) joints. The improved mechanism combines the advantages of coaxial base mounting (as opposed to noncoaxial and/or nonbase mounting) of actuators, plus the advantages of closed-loop (as opposed to open-loop) linkages in such a way as to afford a simplification (in comparison with other linkages) of inverse kinematics. Simplification of the kinematics reduces the computational burden incurred in controlling the manipulator.

In the general case of a two-degree-of-freedom manipulator with two rotary actuators, the inverse kinematic problem is to find the rotary-actuator angles needed to place the end effector at a specified location, velocity, and acceleration in the plane of motion. In the case of a typical older manipulator mechanism of this type, the solution of the inverse kinematic problem involves much computation because what one seeks is the coordinated positions, velocities, and accelerations of the two manipulators, and these coordinates are kinematically related to each other and to the required motion in a complex way.

In the improved mechanism, the task of coordination is greatly simplified by simplification of the inverse kinematics; the motion of the end effector is easily resolved into a component that is radial and a component that is tangential to a circle that runs through the end effector and is concentric with the rotary actuators.

If rotary actuator 2 is held stationary, while rotary actuator 1 is turned, then link D slides radially in the prismatic joint, causing the end effector to move radially. If both rotary actuators are turned together, then there is no radial motion; instead, the entire linkage simply rotates as a rigid body about the actuator axis, so that the end effector moves tangentially. Thus, the task of coordination is reduced to a simple decision to (a) rotate actuator 1 only to obtain radial motion, (b) rotate both actuators together to obtain tangential motion, or (c) rotate the actuators differentially according to a straightforward kinematic relationship to obtain a combination of radial and axial motion.

This work was done by Farhad Tahmasebi of **Goddard Space Flight Center**.



The Improved Mechanism affords a simplification of kinematics: Whereas the coordination of actuator motions necessary to obtain specified end-effector motions in the older mechanisms is a complex task, it is a relatively simple task in the improved mechanism.

TOOL-CHANGING MECHANISM FOR ROBOT

A tool is handed off securely between an end effector and a holster.

Goddard Space flight Center, Greenbelt, Maryland

Figure 1 is a partially exploded view of a tool-changing mechanism for robotic applications. The mechanism effects secure handoff of the tool between the end effector of the robot and a yoke in which the tool is stowed when not in use. The mechanism can be operated in any orientation in normal or low gravitation. Unlike some other robotic tool-changing mechanisms, this one imposes fewer constraints on the design of the robot and on the tool because it is relatively compact. Moreover, it does not require the large insertion forces and the large actuators that would be needed to produce them. Also, it can be stored in zero g and can survive launch loads.

A tool interface assembly is affixed to each tool and contains part of the tool-changing mechanism. The tool is stowed by (1) approximately aligning the tips of the yoke arms with flared openings of the holster guides on the tool interface assembly, (2) sliding the assembly onto the yoke arms, which automatically enforce fine alignment because of the geometric relationship between the mating surfaces of the yoke-arm wheels and the holster guide, (3) locking the assembly on the holster by pushing wing segments of a captured nut (this is described more fully later) into chamfered notches in the yoke arms, and (4) releasing the end effector from the tool interface assembly.

The end effector includes a male splined shaft (not shown in Fig. 1) that is spring-loaded to protrude downward. A motor rotates the male splined shaft via a splined drive shaft that mates with a splined bore in the shank of the male splined shaft. The sequence of movements in which the end effector takes the tool from the holster begins with the movement of the end effector into a position in which its alignment recesses can engage the mating blocks on the tool interface assembly. The end effector is then pushed downward into contact with the tool interface assembly. Meanwhile, the male splined shaft is rotated until the spring force can push it through the opening in the splined female end of a driven bolt, and an alignment cone at the end of the splined male shaft bottoms in a conical hole in the female end of the driven bolt (see Fig. 2)

Assuming that the thread on the driven bolt is right handed, the male splined shaft is rotated clockwise until a vertical spline on this shaft engages a tab in the driven bolt. At that location the shaft and bolt rotate together. As the rotation continues, the driven bolt moves downward in a captive nut until the mating splined surfaces on the male splined shaft and driven bolt make contact. This prevents further downward movement of the driven bolt.

As the rotation continues, the captive nut moves upward. The wing segments mentioned previously are then pulled up, out of the chamfered slots on the yoke

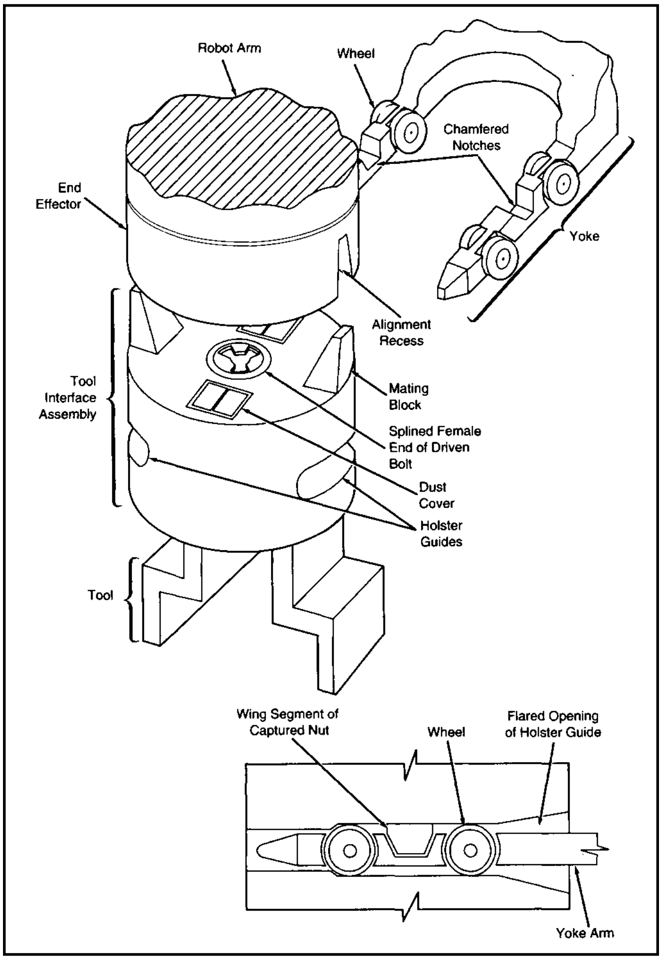


Fig. 1 This tool-changing mechanism operates with relatively small contact forces and is relatively compact.

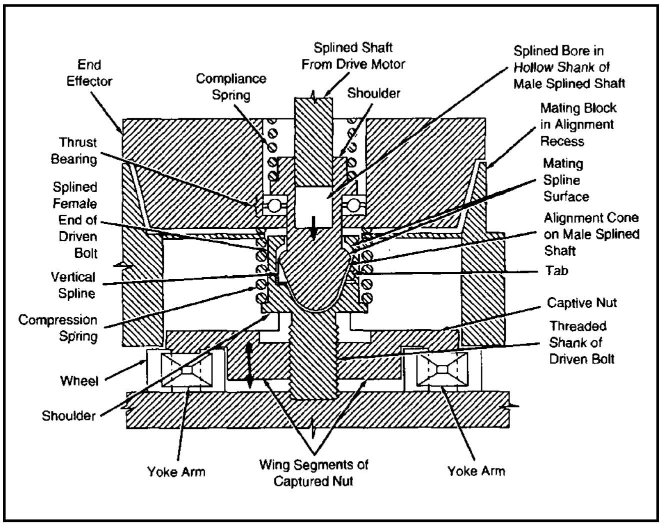


Fig. 2 This end effector and tool interface assembly is shown in its initial mating configuration, immediately before the beginning of the sequence of motions that release the tool from the yoke and secure it to the end effector.

arms, so that the tool interface plate can then be slid freely off of the yoke. Simultaneously, two other wing segments of the captured nut (not shown) push up sets of electrical connectors, through the dust covers, to mate with electrical connectors in the end effector. Once this motion is completed, the tool is fully engaged with the end effector and can be slid off the yoke. To release the tool from the end effector and lock it on the yoke (steps 3 and 4 in the second paragraph), this sequence of motions is simply reversed.

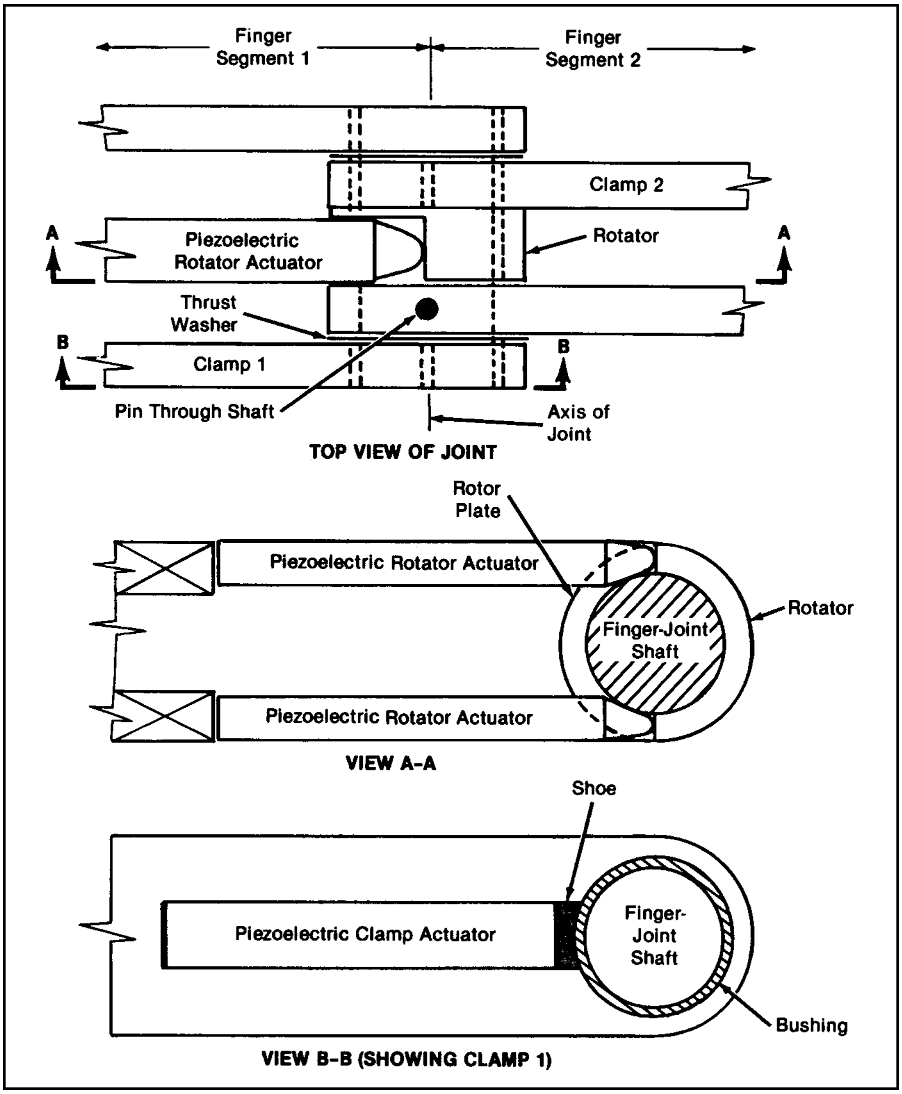
This work was done by John M. Vranish of **Goddard Space Flight Center**.

PIEZOELECTRIC MOTOR IN ROBOT FINGER JOINT

A direct drive unit replaces a remote electromagnetic motor.
Marshall Space Flight Center, Alabama

A robotic finger contains an integral piezoelectric motor. In comparison with a robotic finger actuated by remote motors via tendonlike cables, this robotic finger is simpler and can therefore be assembled, disassembled, and repaired more easily. It is also more reliable and contains more internal space that can be allocated for additional sensors and control circuitry.

The finger (see figure) includes two piezoelectric clamps and a piezoelectric-rotator subassembly. Each clamp is composed of a piezoelectric actuator, a concave shoe, and a thin bushing with an axial slit. A finger-joint shaft fits in the bushing. When the actuator in a clamp is de-energized, the shaft is free to rotate in the bushing. When the same actuator is energized, it expands and pushes the shoe against the bushing. This action clamps the shaft. (The slit in the bushing allows it to flex so that more actuator force acts on the shaft and is not wasted in deforming the bushing.)



Each piezoelectric clamp grasps a shaft when energized. The piezoelectric rotor turns the shaft in small increments as it is alternately clamped and unclamped.

The piezoelectric-rotor subassembly includes a pair of piezoelectric actuators and a component simply called the rotator, which is attached to the bushing in clamp 2. The upper rotator actuator, when energized, pushes the rotator a fraction of a degree clockwise. Similarly, when the lower rotator is energized, it pushes the rotator a fraction of a degree counterclockwise. The finger-joint shaft extends through the rotator. The two clamps are also mounted on the same shaft, on opposite sides of the rotator. The rotator actuators are energized alternately to impart a small back-and-forth motion to the rotator. At the same time, the clamp actuators are energized alternately in such a sequence that the small oscillations of therotator accumulate into a net motion of the shaft (and the finger segment attached to it), clockwise or counterclockwise, depending on whether the shaft is clamped during clockwise or counterclockwise movement of the rotator.

The piezoelectric motor, including lead wires, rotator-actuator supports, and actuator retainers, ads a mass of less than 10 grams to the joint. The power density of the piezoelectric motor is much grater than that of the electromagnetic motor that would be needed to effect similar motion. The piezoelectric motor operates at low speed and high torque—characteristics that are especially suitable for robots.

This work was done by Allen R Grahn of Bonneville Scientific, Inc., for **Marshall Space Flight Center**.

SIX-DEGREE-OF-FREEDOM PARALLEL MINIMANIPULATOR

Advantages include greater stiffness and relative simplicity.

Goddard Space Flight Center, Greenbelt, Maryland

Figure 1 illustrates schematically a six-degree-of-freedom manipulator that produces small, precise motions and that includes only three inextensible limbs with universal joints at their ends. The limbs have equal lengths and can be said to act in parallel in that they share the load on a manipulated platform. The mechanism is therefore called a "six-degree-of-freedom parallel minimanipulator." The minimanipulator is designed to provide high resolution and high stiffness (relative to the other mechanisms) for fine control of position and force in a hybrid form of serial/parallel-manipulator system.

Most of the six-degree-of-freedom parallel manipulators that have been proposed in the past contain six limbs, and their direct kinematic analyses are very complicated. In contrast, the equations of the direct kinematics of the present minimanipulator can be solved in closed form. Furthermore, in comparison with a typical six-degree-of-freedom parallel manipulator, the present minimanipulator can be made of fewer parts, the probability of mechanical interference between its limbs is smaller, its payload capacity can be made greater, and its actuators, which are base-mounted, can be made smaller.

The upper ends of the limbs are connected to the manipulated platform by universal (two-degree-of-freedom) joints. The lower end of each limb is connected via a universal (two-degree-of-freedom) rotary joint to a two-degree-of-freedom driver. The drivers are mounted directly on the baseplate, without any intervening power-transmission devices, like gears or belts, that could reduce stiffness and precision.

The position and orientation of the manipulated platform is governed uniquely, in all six degrees of freedom, by the positions of the drivers on the baseplate. Examples of two-degree-of-freedom drivers include bi-directional linear stepping motors, *x-y* positioning tables, five-bar linkages driven by rotary actuators, and pantographs. Figure 2 shows an example of a baseplate equipped with pantograph drivers. The position of each universal joint C_i (where i = 1, 2, or 3) is controlled by moving either or both of sliders A_i and B_i in their respective guide slots. The displacement reduction provided by the pantograph linkage and the inextensible limbs is equivalent to an increase in mechanical advantage; it increases the stiffness and resolution available at the manipulated platform.

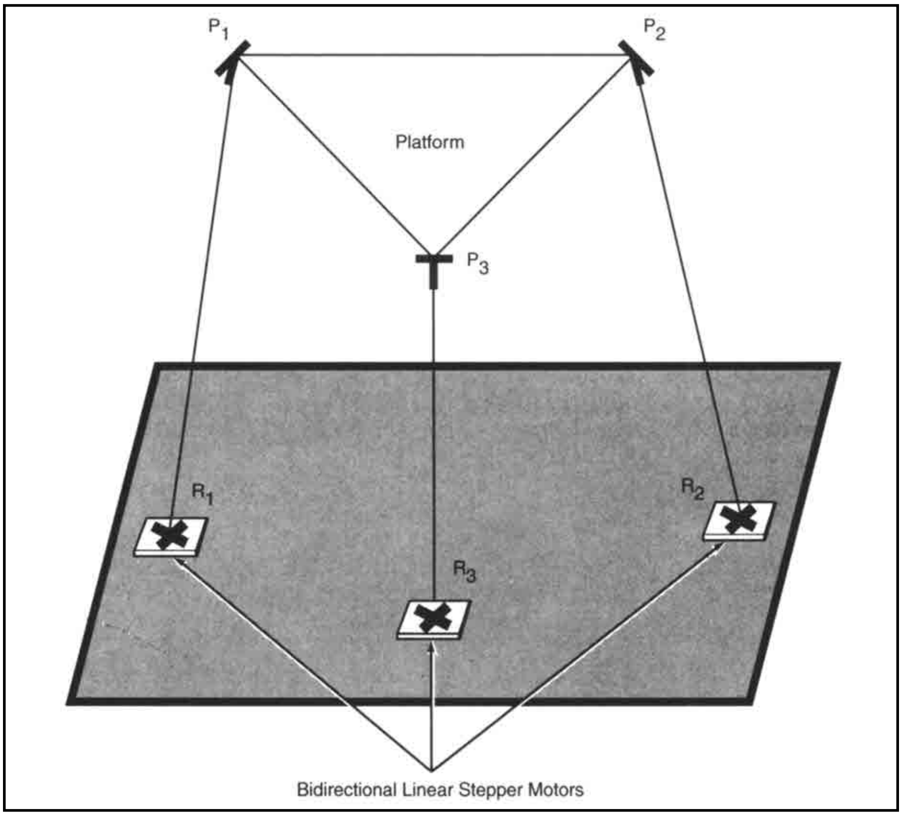


Fig. 1 The **six-degree-of-freedom parallel minimanipulator** is stiffer and simpler than earlier six-degree-of-freedom manipulators, partly because it includes only three inextensible limbs.

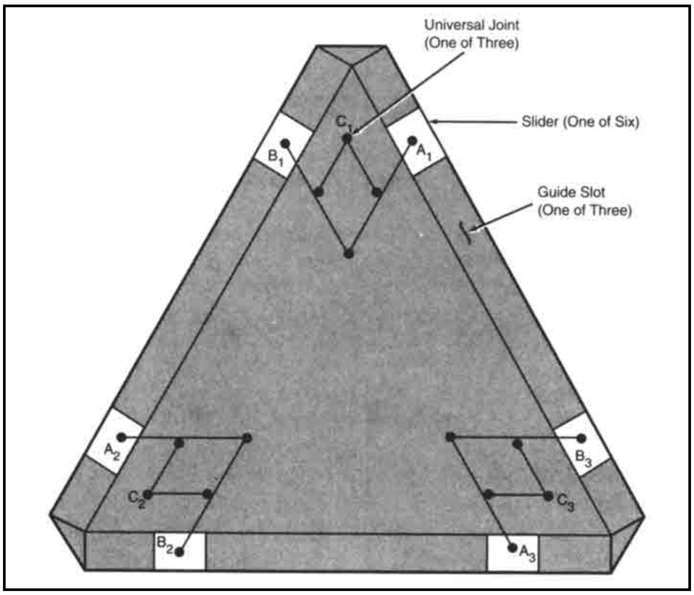
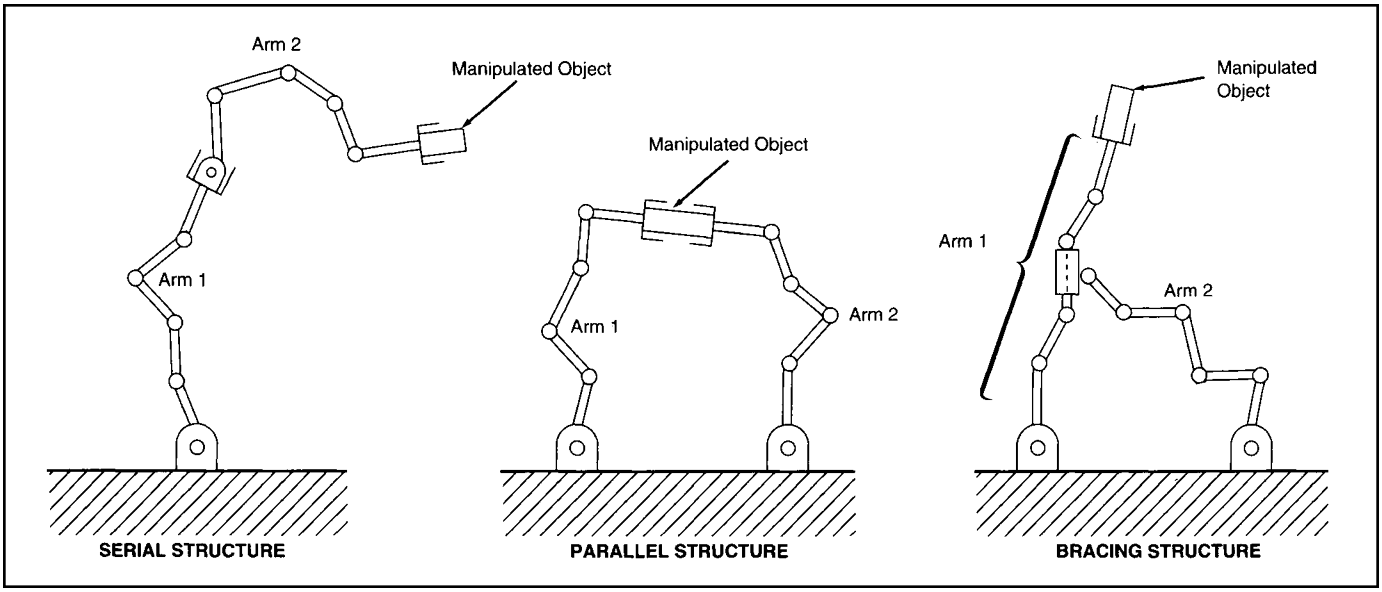


Fig. 2 Three pantographs on the baseplate control the positions of the universal joints at C_1 and thereby control the position and orientation of the manipulated platform.

This work was done by Farhad Tahmasebi and Lung-Web Tsai of **Goddard Space Flight Center**.

SELF-RECONFIGURABLE, TWO-ARM MANIPULATOR WITH BRACING

Structure can be altered dynamically to suit changing tasks.
NASA's Jet Propulsion Laboratory, Pasadena, California



Alternative structures of cooperating manipulator arms can be selected to suit changing tasks.

A proposed two-arm robotic manipulator would be capable of changing its mechanical structure to fit a given task. Heretofore, the structures of reconfigurable robots have been changed by replacement and/or reassembly of modular links. In the proposed manipulator, there would be no reassembly or replacement in the conventional sense: instead, the arms would be commanded during operation to assume any of a number of alternative configurations.

The configurations (see figure) are generally classified as follows: (1) serial structure, in which the base of arm 1 is stationary, the tip of arm 1 holds the base of arm 2, and the tip of arm 2 holds the manipulated object; (2) parallel structure, in which the bases of both arms are stationary and the tips of both arms make contact with the manipulated object at two different points; and (3) the bracing structure, in which the basis of both arms are stationary and the tip of arm 2 grasps some intermediate point along the length of arm 1. the serial and parallel structures can be regarded as special cases of the bracing structure. Optionally, each configuration could involve locking one or more joints of either or both arms, and the bracing contact between the two arms could be at a fixed position of arm 1 or else allowed to slide along a link of arm 1.

The performances of the various configurations can be quantified in terms of quantities called "dual-arm manipulabilities," and "dual-arm resistivities." Dual-arm manipulabilities are defined on the basis of kinematic and dynamic constraints; dual-arm resistivities are defined on the basis of static-force constraints. These quantities serve as measures of how well such dextrous-bracing actions as relocation of the bracing point, sliding contact, and locking of joints affect the ability of the dual-arm manipulator to generate motions and to apply static forces.

Theoretical study and computer simulation have shown that dextrous bracing yields performance characteristics that vary continuously and widely as the bracing point is moved along the braced arm. In general, performance characteristics lie between those of the serial and parallel structures. Thus, one can select configurations dynamically, according to their performance characteristics, to suit the changing requirements of changing tasks.

This work was done by Sukhan Lee and Sungbok Kim of Caltech for **NASA's Jet Propulsion Laboratory**.

IMPROVED ROLLER AND GEAR DRIVES FOR ROBOTS AND VEHICLES

One type is designed to eliminate stick/slip, another to eliminate reaction torque.

Lewis Research Center, Cleveland, Ohio

Two types of gear drives have been devised to improve the performances of robotic mechanisms. One type features a dual-input/single-output differential-drive configuration intended to eliminate stick/slip motions; the other type features a single-input/dual-angular-momentum-balanced-output configuration intended to eliminate reaction torques.

Stick/slip motion can degrade the performance of a robot because a robotic control system cannot instantaneously correct for a sudden change between static and dynamic friction. Reaction torque arises in a structure that supports a mechanism coupled to a conventional gear drive, and can adversely affect the structure, the mechanism, or other equipment connected to the structure or mechanism.

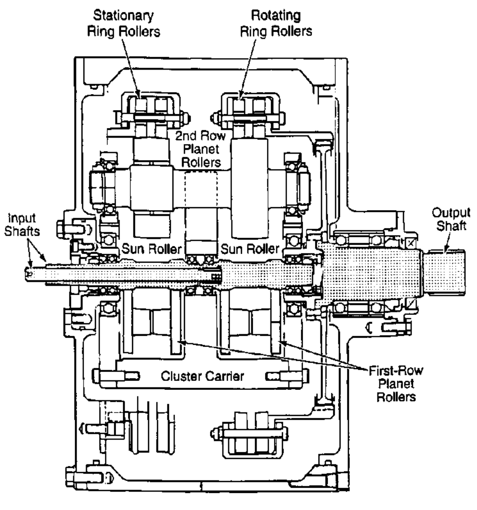
In a drive of the differential type, the two input shafts can be turned at different speeds and, if necessary, in opposite directions, to make the output shaft turn in the forward or reverse direction at a desired speed. This is done without stopping rotation of either input shaft, so that stick/slip does not occur. In a drive of the angular-momentum-balanced type, turning the single input shaft causes the two output shafts to rotate at equal speeds in opposite directions.

The figure schematically illustrates one of two drives of the differential type and one drive of the angular-momentum-balanced type that have been built and tested. Each of the differential drives is rated at input speeds up to 295 radians per second (2,800 r/min), output torque up to 450 N·m (4,000 lb-in.), and power up to 5.6 kW (7.5 hp). The maximum ratings of the angular-momentum-balanced drive are input speed of 302 radians per second (2,880 r/min), dual output torques of 434 N·m (3,840 lb-in.) each, and power of 10.9 kW (14.6 hp).

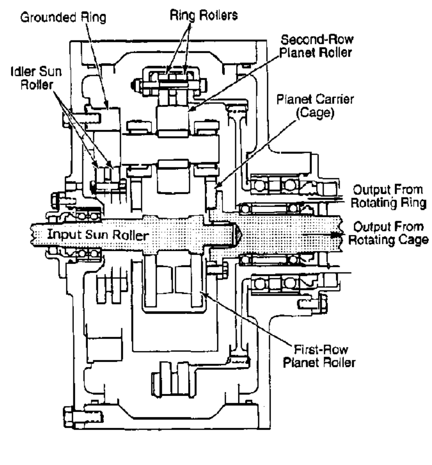
Each differential drive features either (as explained in the next two sentences) a dual roller-gear or a roller arrangement with a sun gear, four first-row planet gears, four second-row planet gears, and a ring gear. One of the differential drives contains a planetary roller-gear system with a reduction ratio (measured with one input driving the output while the other input shaft remains stationary) of 29.23:1. The other differential drive (the one shown in the figure) contains a planetary roller system with a reduction ratio of 24:1. The angular-momentum-balanced drive features a planetary roller system with five first- and second-row planet gears and a reduction ratio (the input to each of the two outputs) of 24:1. The three drives were subjected to a broad spectrum of tests to measure linearity, cogging, friction, and efficiency. All three drives operated as expected kinematically, exhibiting efficiencies as high as 95 percent.

Drives of the angular-momentum-balanced type could provide a reaction-free actuation when applied with proper combinations of torques and inertias coupled to output shafts. Drives of the differential type could provide improvements over present robotic transmissions for applications in which there are requirements for extremely smooth and accurate torque and position control, without inaccuracies that accompany stick/slip. Drives of the differential type could also offer viable alternatives to variable-ratio transmissions in applications in which output shafts are required to be driven both forward and in reverse, with an intervening stop. A differential transmission with two input drive motors could be augmented by a control system to optimize input speeds for any requested output speed; such a transmission could be useful in an electric car.

This work was done by William J. Anderson and William Shipitalo of Nastec, Inc., and Wyatt Newman of Case Western Reserve University for **Lewis Research Center**.



DIFFERENTIAL DRIVE

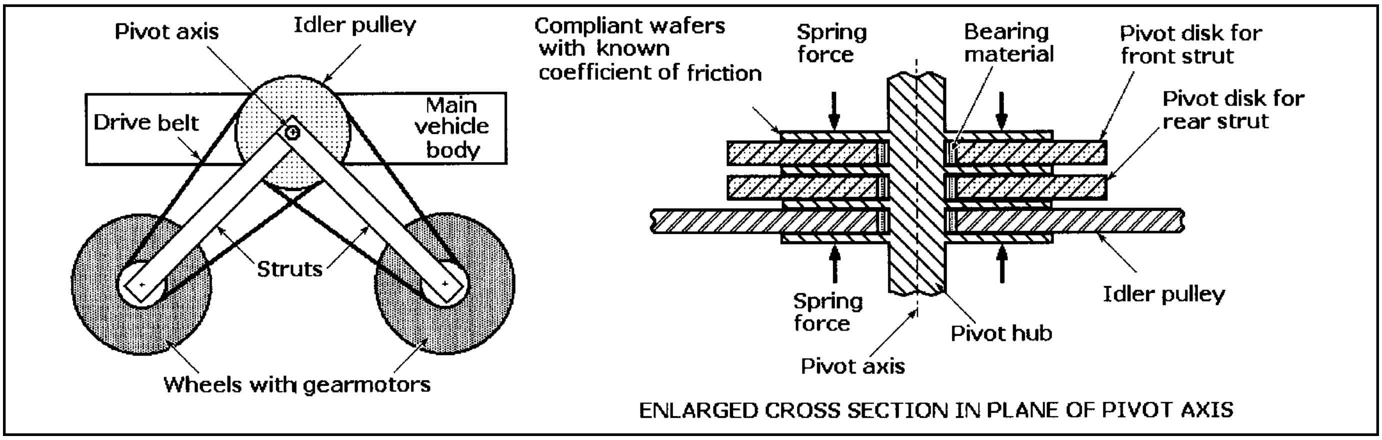


ANGULAR-MOMENTUM-BALANCED DRIVE

These Improved Gear Drives offer advantages for control of traction and rotary actuation in robots. In addition, drives of the differential type could be used in variable-speed transmissions in automobiles.

ALL-TERRAIN VEHICLE WITH SELF-RIGHTING AND POSE CONTROL

Wheels driven by gearmotors are mounted on pivoting struts.
NASA's Jet Propulsion Laboratory, Pasadena, California



Each wheel Is driven by a dedicated gearmotor and is coupled to the idler pulley. The pivot assembly imposes a constant frictional torque T, so that it is possible to (a) turn both wheels in unison while both struts remain locked, (b) pivot one strut, or (c) pivot both struts in opposite directions by energizing the gearmotors to apply various combinations of torques T/2 or T.

A small prototype robotic all-terrain vehicle features a unique drive and suspension system that affords capabilities for self righting, pose control, and enhanced maneuverability for passing over obstacles. The vehicle is designed for exploration of planets and asteroids, and could just as well be used on Earth to carry scientific instruments to remote, hostile, or otherwise inaccessible locations on the ground. The drive and suspension system enable the vehicle to perform such diverse maneuvers as flipping itself over, traveling normal side up or upside down, orienting the main vehicle body in a specified direction in all three dimensions, or setting the main vehicle body down onto the ground, to name a few. Another maneuver enables the vehicle to overcome a common weakness of traditional all-terrain vehicles—a limitation on traction and drive force that makes it difficult or impossible to push wheels over some obstacles: This vehicle can simply lift a wheel onto the top of an obstacle.

The basic mode of operation of the vehicle can be characterized as four-wheel drive with skid steering. Each wheel is driven individually by a dedicated gearmotor. Each wheel and its gearmotor are mounted at the free end of a strut that pivots about a lateral axis through the center of gravity of the vehicle (see figure). Through pulleys or other mechanism attached to their wheels, both gearmotors on each side of the vehicle drive a single idler disk or pulley that turns about the pivot axis.

The design of the pivot assembly is crucial to the unique capabilities of this system. The idler pulley and the pivot disks of the struts are made of suitably chosen materials and spring-loaded together along the pivot axis in such a way as to resist turning with a static frictional torque T; in other words, it is necessary to apply a torque of T to rotate the idler pulley or either strut with respect to each other or the vehicle body.

During ordinary backward or forward motion along the ground, both wheels are turned in unison by their gearmotors, and the belt couplings make the idler pulley turn along with the wheels. In this operational mode, each gearmotor contributes a torque T/2 so that together, both gearmotors provide torque T to overcome the locking friction on the idler pulley. Each strut remains locked at its preset angle because the torque T/2 supplied by its motor is not sufficient to overcome its locking friction T.

If it is desired to change the angle between one strut and the main vehicle body, then the gearmotor on that strut only is energized. In general, a gearmotor acts as a brake when not energized. Since the gearmotor on the other strut is not energized and since it is coupled to the idler pulley, a torque greater than T would be needed to turn the idler pulley. However, as soon as the gearmotor on the strut that one desires to turn is energized, it develops enough torque (T) to begin pivoting the strut with respect to the vehicle body.

It is also possible to pivot both struts simultaneously in opposite directions to change the angle between them. To accomplish this, one energizes the gearmotors to apply equal and opposite torques of magnitude T: The net torque on the idler pulley balances out to zero, so that the idler pulley and body remain locked, while the applied torques are just sufficient to turn the struts against locking friction. If it is desired to pivot the struts through unequal angles, then the gearmotor speeds are adjusted accordingly.

The prototype vehicle has performed successfully in tests. Current and future work is focused on designing a simple hub mechanism, which is not sensitive to dust or other contamination, and on active control techniques to allow autonomous planetary rovers to take advantage of the flexibility of the mechanism.

This work was done by Brian H. Wilcox and Annette K. Nasif of Caltech for **NASA's Jet Propulsion Laboratory**.