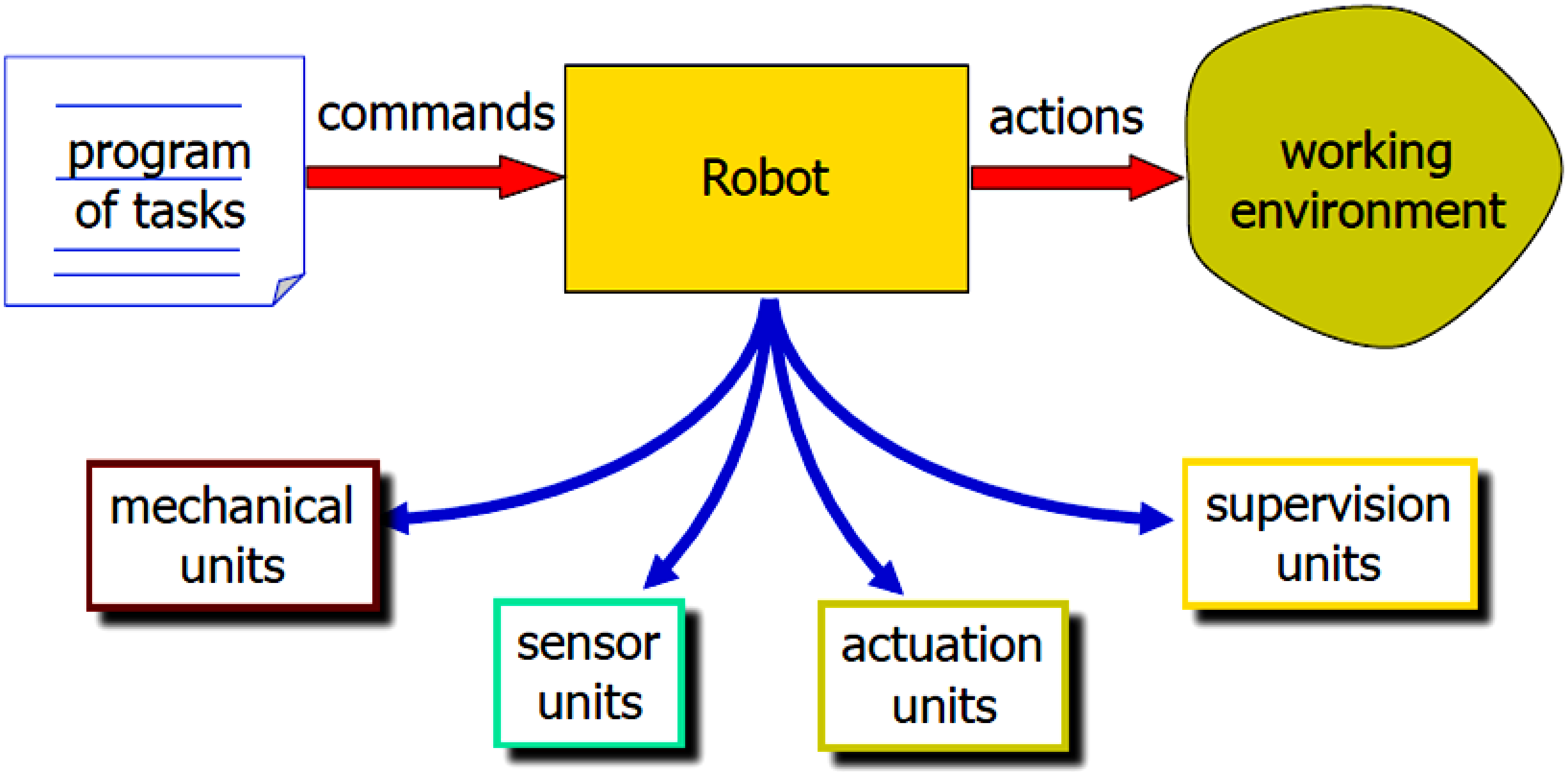
Robot Actuators

Robot as a system



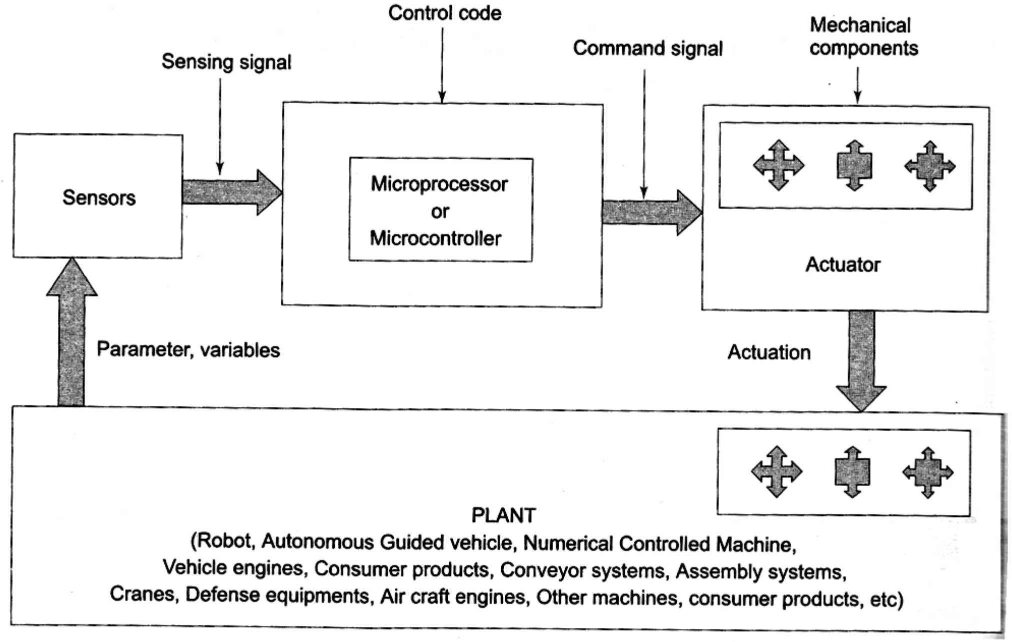
Functional units of a robot

- mechanical units (robot arms)
  - rigid links connected through *rotational* or *prismatic* joints (each 1 dof)
  - mechanical subdivisions:
    - *supporting structure* (mobility), *wrist* (dexterity), *end-effector* (task execution, e.g., manipulation)
- sensor units
  - proprioceptive (internal robot state: position and velocity of the joints)
  - exteroceptive (external world: force and proximity, vision, ...)
- actuation units
  - motors (*electrical, hydraulic, pneumatic*)
  - motion control algorithms
- supervision units
  - task planning and control
  - artificial intelligence and reasoning

Introduction

Actuators

- Actuation is the process of conversion of energy to mechanical form. A device that accomplishes this conversion is called actuator.
- Actuator plays a very important role while implementing control. The controller provides command signal to the actuator for actuation.
- The control codes aims at “ deriving the actuator when an event has occurred”



Simple sensor actuator connection [Mahalik, 2003]

Introduction

- Actuators are the muscles of robots. There are many types of actuators available depending on the load involved. The term load is associated with many factors including force, torque, speed of operation, accuracy, precision and power consumption:

1- Electric Motors

- Servomotors
- Stepper motors
- Direct-drive electric motors

2- Hydraulic actuators

3- Pneumatic actuators

4-Shape memory metal actuators

5- Magnetostrictive actuators.

- Electromechanical actuators convert electrical energy into mechanical energy. Magnetism is the basis of their principle of operation. They are DC, AC and stepper motors.
- DC motors require a direct current or voltage source as the input signals.
- AC motors require an alternating current or voltage source

Introduction

- Stepper motors have capability of achieving precision angular rotation in both directions and are commonly employed to accommodate digital control technology.

- Hydraulic and pneumatic actuators are under fluid power actuators. Fluid power refers to energy that is transmitted via a fluid under pressure. When a pressure is applied to a confined chamber containing a piston, the piston will exert a force causing a motion. The piston will move if the difference in force across the piston is larger than the total load plus the friction forces.

- Materials which undergo some sort of transformations through physical interaction, are referred to as active materials. Piezoelectric (voltage-load), shape-memory alloys (react to heat), magnetostrictive are examples of these materials.

Introduction

Characteristics of actuating systems

1- Weight, Power-to-weight Ratio, Operating pressure

- Stepper motors are generally heavier than servomotors for the same power.
- The high the voltage of electric motors, the better power-to-weight ratio.
- Pneumatic systems delivers the lowest power-to-weight ratio (100-120 psi)
- Hydraulic systems have the highest power-to-weight ratio (55-5000 psi). In these systems, the weight is actually composed of two portions. One is the hydraulic actuators, and the other is the hydraulic power unit (pump, cylinders, rams, reservoirs, filter, and electric motor). If the power unit must also move with the robot, the total power-to-weight ratio will be much less.

2- Stiffness versus Compliance

- Stiffness is the resistance of a material against deformation. The stiffer the system, the larger the load that is needed to deform it. Conversely, the more compliant the system the easier it deforms under the load.
- Stiffness is directly related to the modulus of elasticity of the material. Hydraulic systems are very stiff and non-compliant while pneumatic systems are easily compressed and thus are compliant.
- Stiff systems have a more rapid response to changing loads and pressures and are more accurate.
- Although stiffness causes a more responsive and more accurate systems, it also creates a danger if all things are not always perfect.

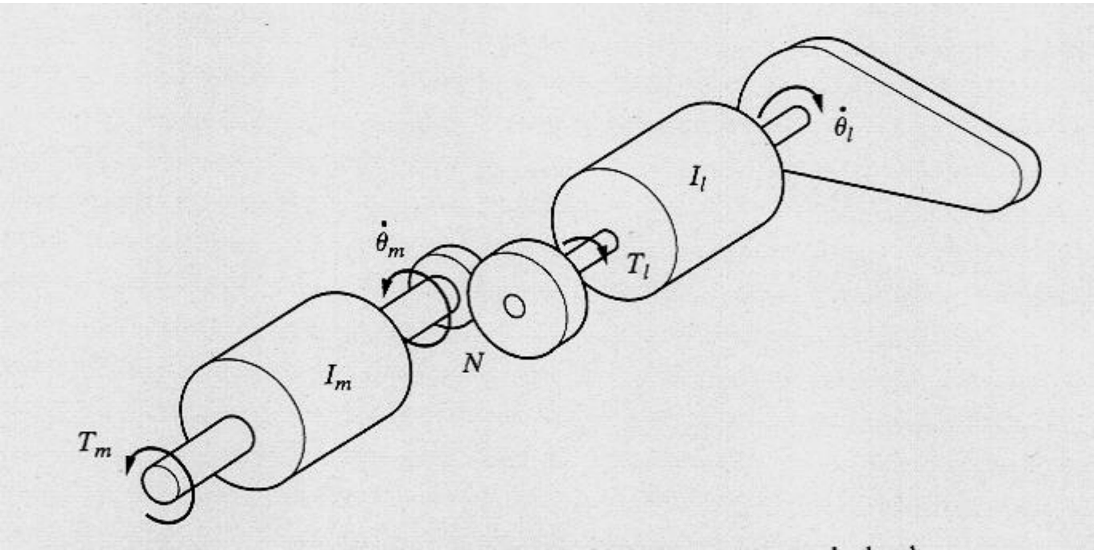
Introduction

3- Use of Reduction Gears

- Hydraulic devices produce very large forces with short stroke. This means that the hydraulic arm may be moved very slightly while delivering its full force. As a result, there is no need to use reduction gear trains to increase the torque and to slow it down to manageable speeds.
- Electric motors rotate at high speeds (up to many thousands of revolution per minute) and must be used in conjunction with reduction gears to increase torque and reduce rotation speed. This will increase the cost, number of parts, backlash, and inertia of the rotating body.

Introduction

- Now suppose that, through a set of reduction gears with ratio of N, a load with inertia , is connected to a motor with Inertia (including inertia of reduction gears), as shown in Figure (6.1). The torque and speed ratio between the motor and the load will be:



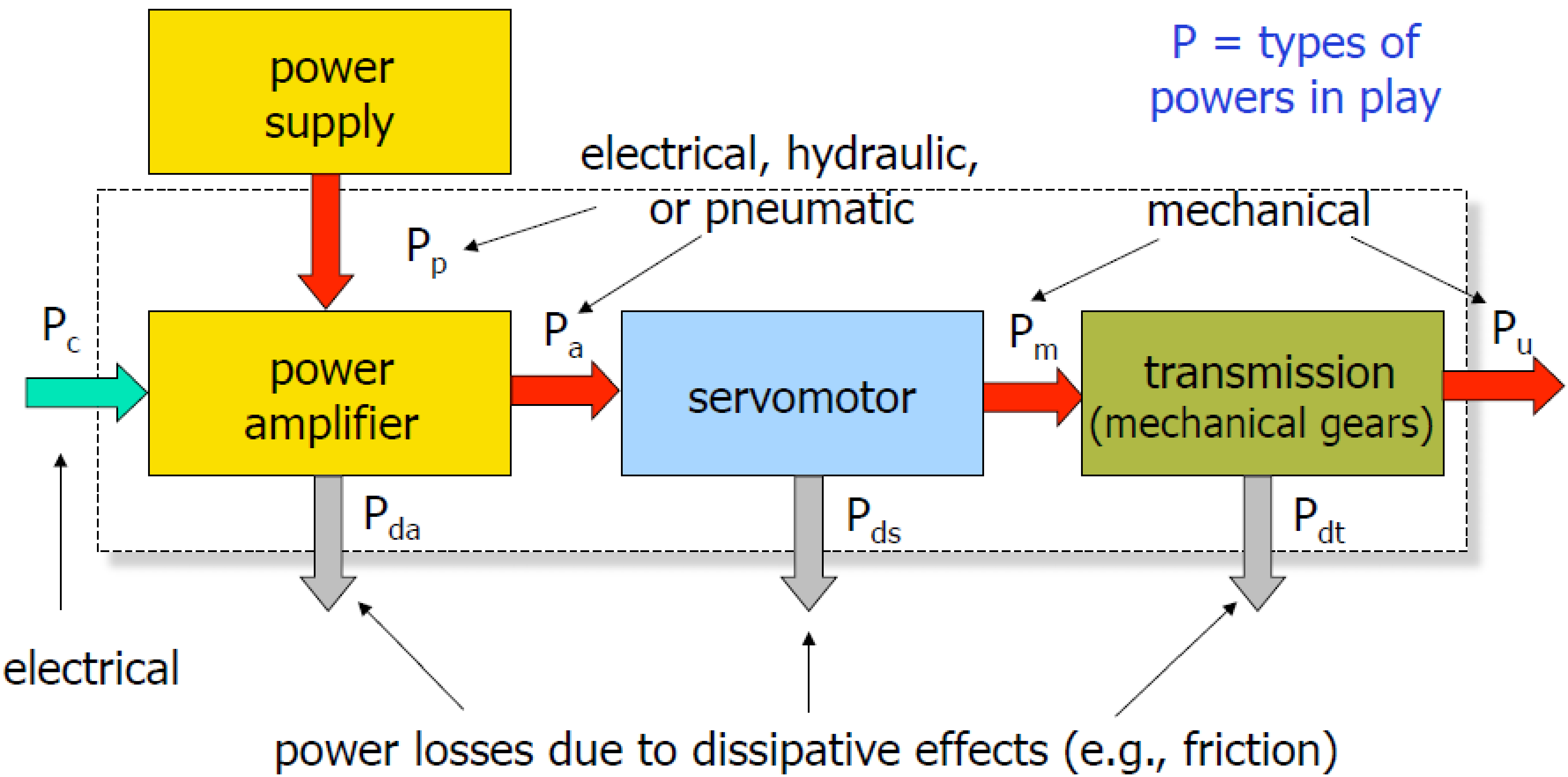
Inertia and torque relationship between a motor and a load

Introduction

TABLE 6.1 SUMMARY OF ACTUATOR CHARACTERISTICS

Hydraulic	Electric	Pneumatic
+ Good for large robots and heavy payload	+ Good for all sizes of robots	+ Many components are usually off-the-shelf
+ Highest power/weight ratio	+ Better control, good for high precision robots	+ Reliable components
+ Stiff system, high accuracy, better response	+ Higher compliance than hydraulics	+ No leaks or sparks
+ No reduction gear needed	+ Reduction gears used reduce inertia on the motor	+ Inexpensive and simple
+ Can work in wide range of speeds without difficulty	+ Does not leak, good for clean room	+ Low pressure compared to hydraulics
+ Can be left in position without any damage	+ Reliable, low maintenance	+ Good for on-off applications and for pick and place
− May leak. Not fit for clean room applications	+ Can be spark-free. Good for explosive environments	+ Compliant systems
− Requires pump, reservoir, motor, hoses, etc.	− Low stiffness	− Noisy systems
− Can be expensive and noisy. Requires maintenance	− Needs reduction gears, increased backlash, cost, weight, etc.	− Require air pressure, filter, etc.
− Viscosity of oil changes with temperature	− Motor needs braking device when not powered. Otherwise, the arm will fall.	− Difficult to control their linear position
− Very susceptible to dirt and other foreign material in oil		− Deform under load constantly
− Low compliance		− Very low stiffness. Inaccurate response
− High torque, high pressure, large inertia on the actuator		− Lowest power to weight ratio

Actuation systems



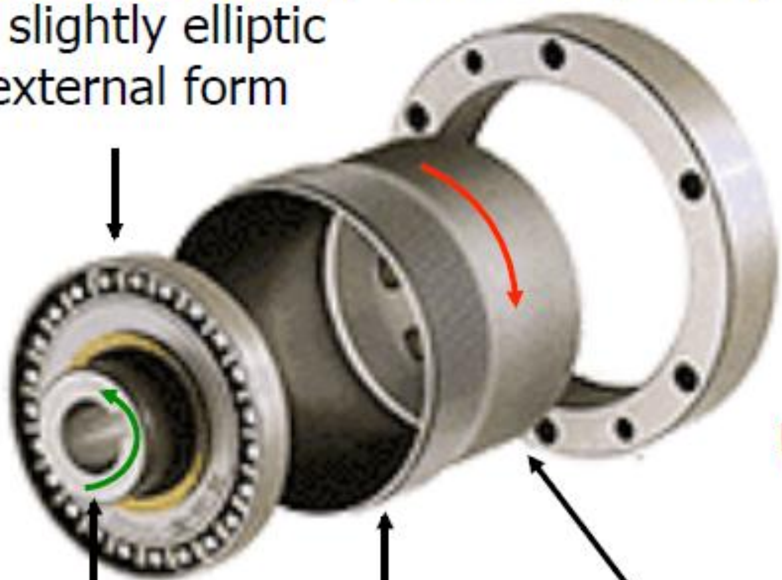
Motion transmission gears

- optimize the transfer of mechanical torque from actuating motors to driven links
- quantitative transformation (from low torque/high velocity to high torque/low velocity)
- qualitative transformation (e.g., from rotational motion of an electrical motor to a linear motion of a link along the axis of a prismatic joint)
- allow improvement of static and dynamic performance by reducing the weight of the actual robot structure in motion (locating the motors remotely, closer to the robot base)

Transmissions in robotics

- spur gears: modify direction and/or translate axis of (rotational or translational) motor displacement
  - problems: deformations, backlash
- lead screws, worm gearing: convert rotational into translational motion (prismatic joints)
  - problems: friction, elasticity, backlash
- toothed belts and chains: dislocate the motor w.r.t. the joint axis
  - problems: compliance (belts) or vibrations induced by larger mass at high speed (chains)
- harmonic drives: compact, in-line, power efficient, with high reduction ratio (up to 150-200:1)
  - problems: elasticity
- transmission shafts: inside the links…

Harmonic drives

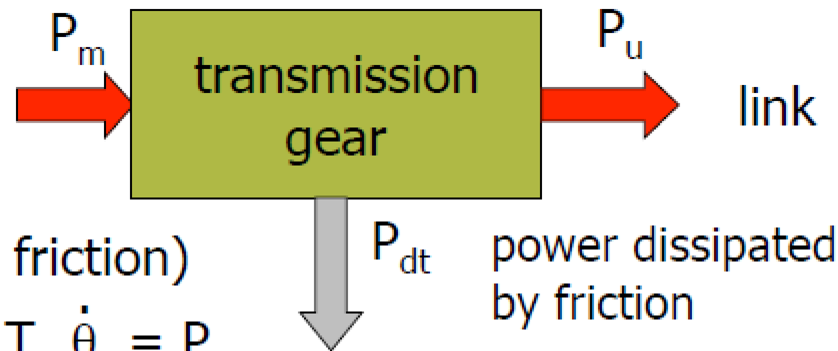


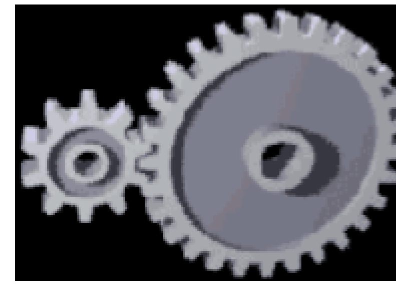
outer #teeth FS = inner #teeth CS - 2

reduction ratio

n = #teeth FS / (#teeth CS - #teeth FS)

Optimal choice of reduction ratio





ideal case (no friction)

$$P_m = T_m \, \dot{\theta}_m = T_u \, \dot{\theta}_u = P_u$$

torque x angular speed

n = reduction ratio ($\gg 1$) $\quad \dot{\theta}_m = n \, \dot{\theta}_u \;\Rightarrow\; T_u = n \, T_m$

to have $\ddot{\theta}_u = a$ (thus $\ddot{\theta}_m = n \, a$), the motor should provide a torque

$$T_m = J_m \, \ddot{\theta}_m + 1/n \, (J_u \, \ddot{\theta}_u) = (J_m \, n + J_u / n) \, a$$

inertia x angular acceleration

for minimizing T_m, we set: $\quad \dfrac{\partial T_m}{\partial n} = (J_m - J_u / n^2) \, a = 0$

$\Rightarrow$ $n = (J_u / J_m)^{1/2}$ "matching" condition between inertias

Desired characteristics for robot servomotors

- low inertia
- high power-to-weight ratio
- high acceleration capabilities
  - variable motion regime, with several stops and inversions
- large range of operational velocities
  - 1 to 1000 turns/min
- high accuracy in positioning
  - at least 1/1000 of a turn
- low torque ripple
  - continuous rotation at low speed
- power: 10W to 10 kW

Servomotors

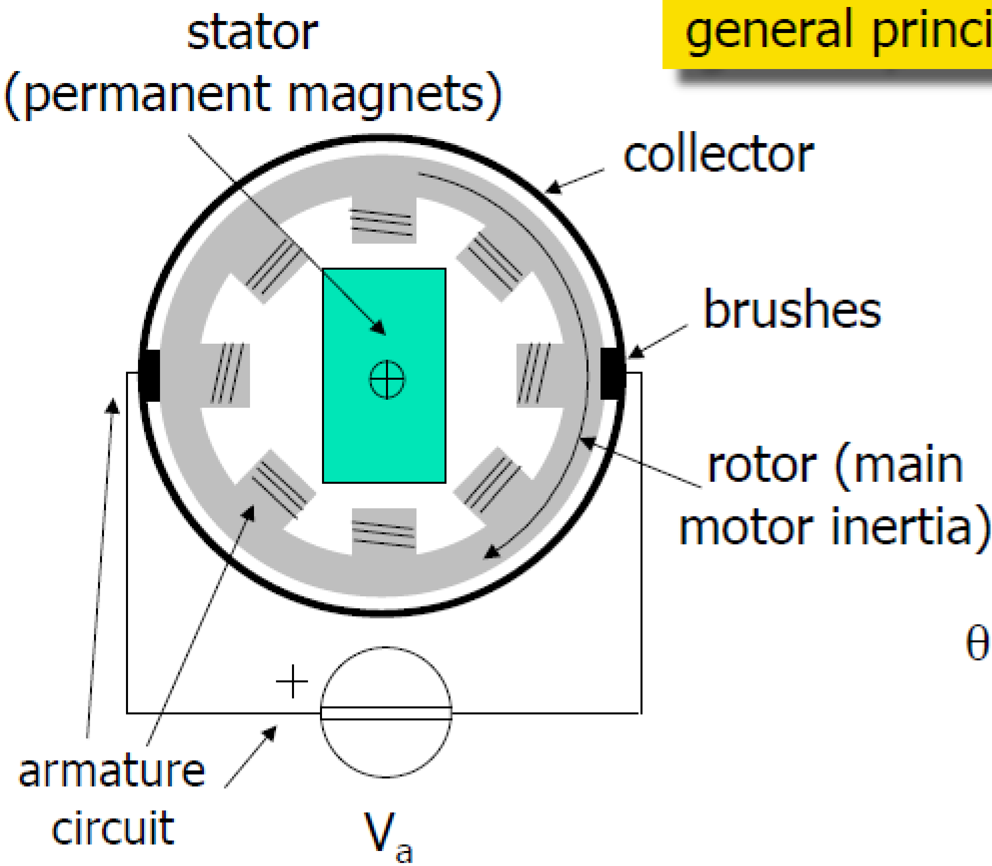
- pneumatic: pneumatic energy (compressor) → pistons or turbines → mechanical energy
  - difficult to control accurately (fluid compressibility changes) → no trajectory control
  - used for opening/closing grippers and tools
- hydraulic: hydraulic energy (accumulation tank) → pumps/valves → mechanical energy
  - advantages: no static overheating, self-lubricated, inherently safe (no sparks), excellent power-to-weight ratio, high torques at low velocity (without reduction gears)
  - disadvantages: needs hydraulic supply, high cost, large size, low power conversion efficiency, increased maintenance, oil leaking

Electrical servomotors

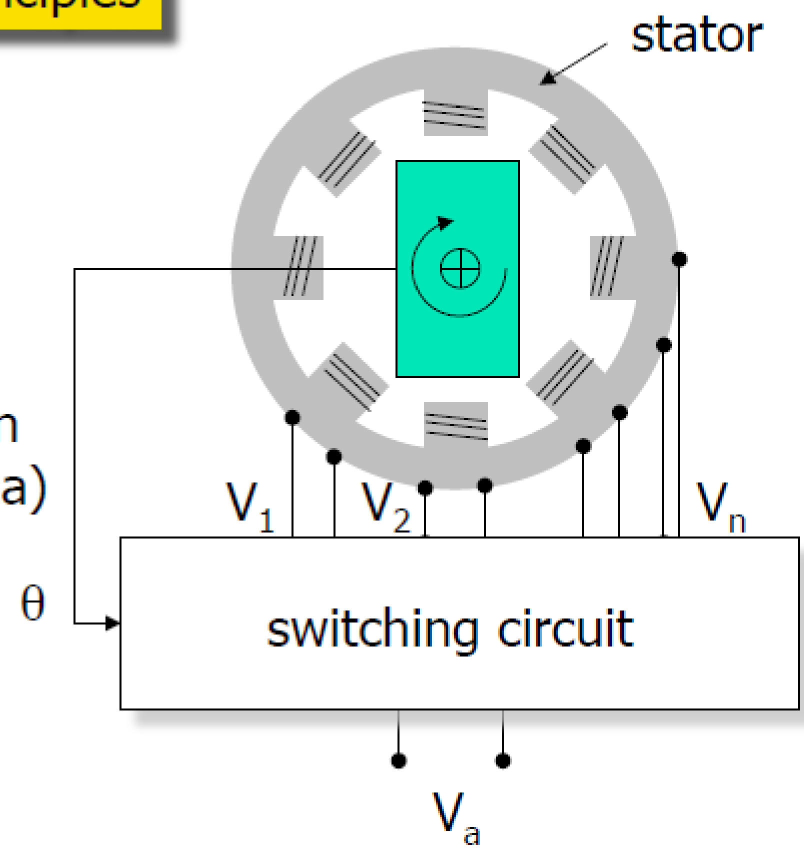
- advantages
  - power supply available everywhere
  - low cost
  - large variety of products
  - high power conversion efficiency
  - easy maintenance
  - no pollution in working environment
- disadvantages
  - overheating in static conditions (in the presence of gravity)
    - use of emergency brakes
  - need special protection in flammable environments

Electrical servomotors for robots

general principles



direct current (DC)



with electronic switches (brushless)

Advantages of brushless motors

- reduced losses, both electrical (due to tension drops at the collector-brushes contacts) and mechanical (friction)
- reduced maintenance (no substitution of brushes)
- easier heat dissipation
- more compact rotor (less inertia and smaller dimensions)

... but indeed a higher cost!

DC electrical motor
mathematical model

electrical balance

Laplace domain
(transfer functions)

mechanical balance

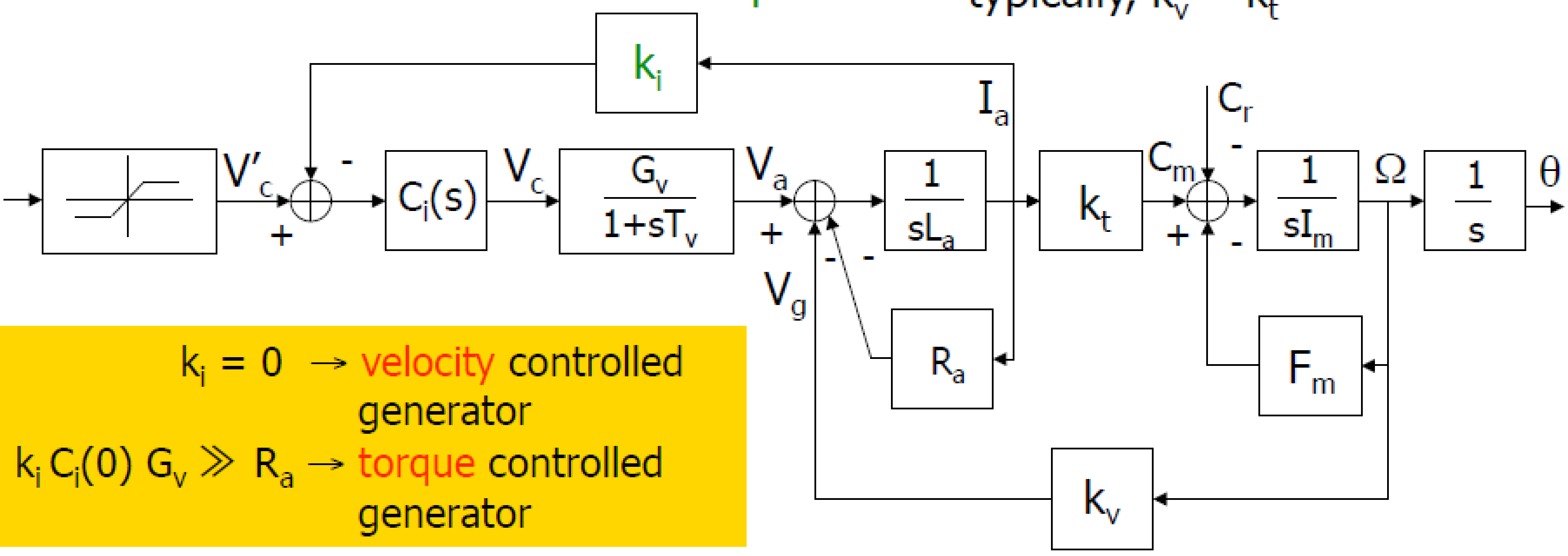
$V_a = (R_a + sL_a)\, I_a + V_g$

$V_g = k_v\, \Omega$

$C_m = (sI_m + F_m)\, \Omega + C_r$

$C_m = k_t\, I_a$

typically, $k_v = k_t$



$k_i = 0 \rightarrow$ velocity controlled generator

$k_i\, C_i(0)\, G_v \gg R_a \rightarrow$ torque controlled generator

Data sheet electrical motors

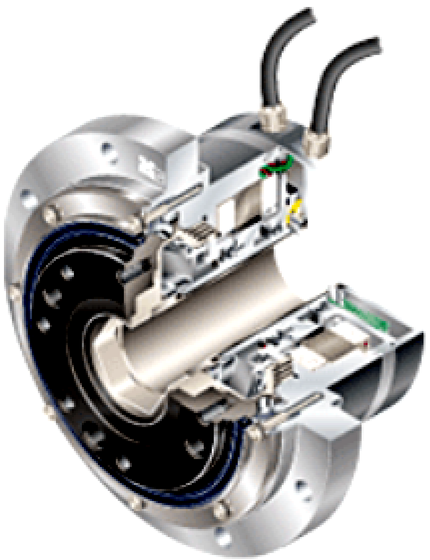
- DC drives

Model of actuator		RHS-14		RHS-17		RHS-20/RFS-20				RHS-25/RFS-25				RHS-32/RFS-32			
		6003	3003	6006	3006	6007	3007	6012	3012	6012	3012	6018	3018	6018	3018	6030	3030
Rated Torque	Inlb	48	69	87	177	106	212	177	266	177	354	266	531	266	531	443	885
	Nm	5.4	7.8	9.8	20	12	24	20	30	20	40	30	60	30	60	50	100
Rated Speed of Rotation	rpm	60	30	60	30	60	30	60	30	60	30	60	30	60	30	60	30
Max. Instant. Torque	Inlb	159	248	301	478	504	743	504	743	885	1416	885	1416	1947	3009	1947	3009
	Nm	18	28	34	54	57	84	57	84	100	160	100	160	220	340	220	340
Max.Speed of Rotation	rpm	100	50	80	40	80	40	80	40	80	40	80	40	80	40	80	40

nominal/peak torques and speeds

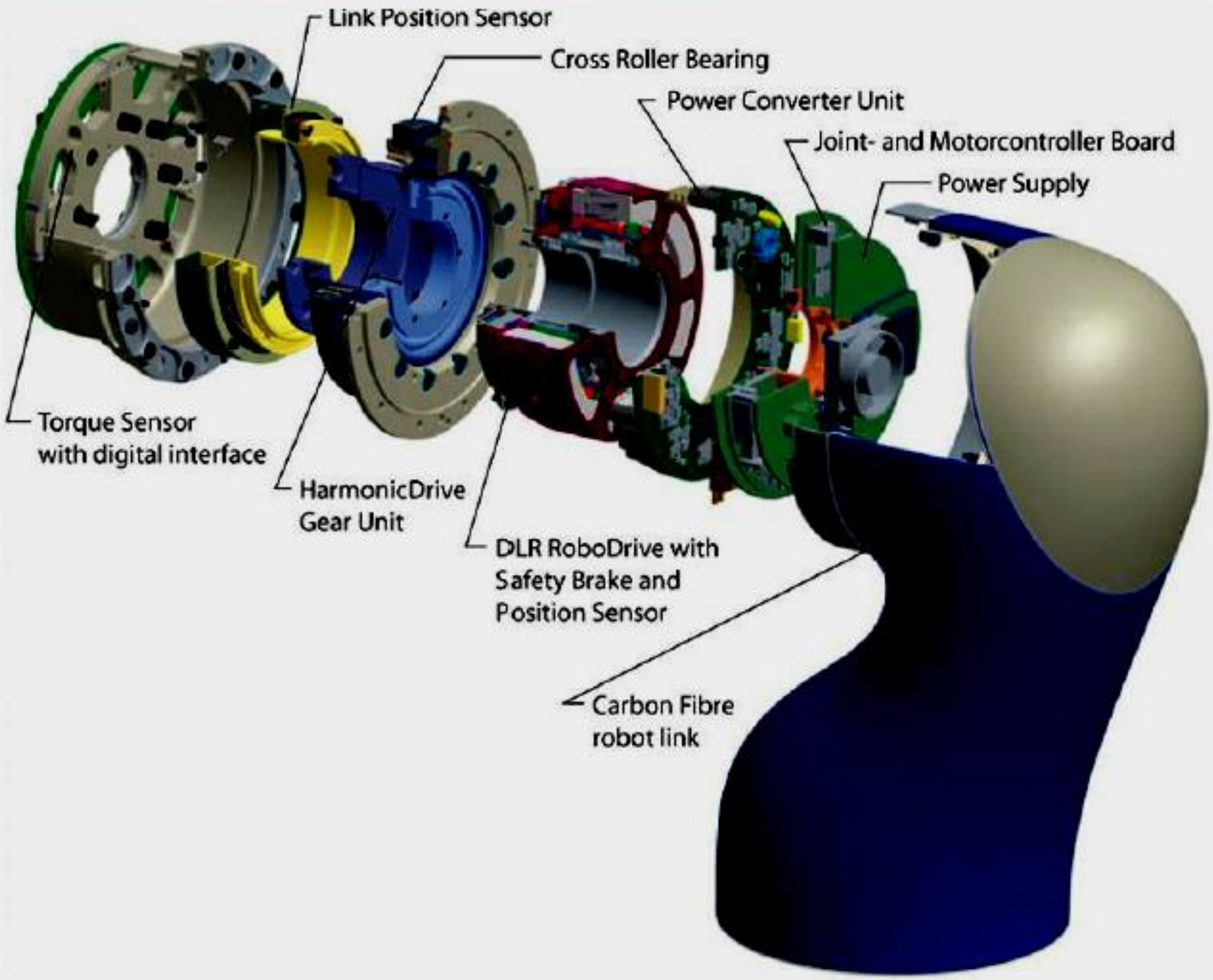
Data sheet electrical motors

- AC drives



	unit	HKM-20-60	HKM-20-30	HKM-25-60	HKM-25-30
Rated Power	Watts	100		200	
Rated Torque	in-lb	115	223	233	440
	N-m	13	26	26	50
Maximum Torque	in-lb	345	700	830	1330
	N-m	39	79	94	150
Rated Speed	r/min	60	30	60	30
Maximum Speed	r/min	80	40	80	40
Current Rated	A	1.8	1.4	4.8	3
Current Max	A	5	4	14	9
Thermal Time Constant	min.				
Gear Reduction Ratio	R:1	50	100	50	100
Output Resolution	P/rev	50,000	100,000	75,000	150,000
	arc sec	26	13	17	9
Absolute Accuracy	+/- arc sec	75	40	60	40

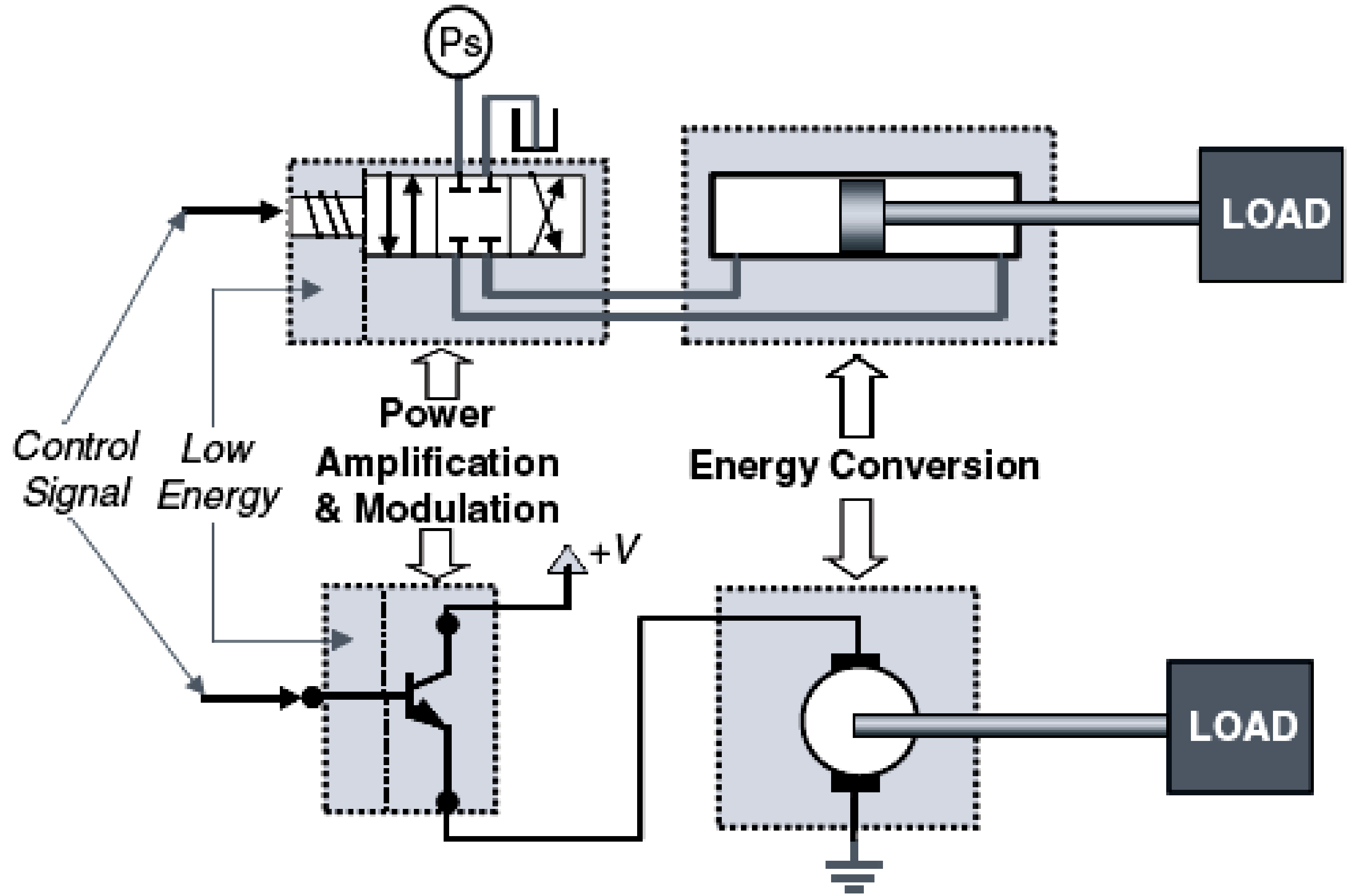
Exploded view of a joint
in the DLR-III robot



Hydraulic Actuators

- A hydraulic system generally consists of the following parts:

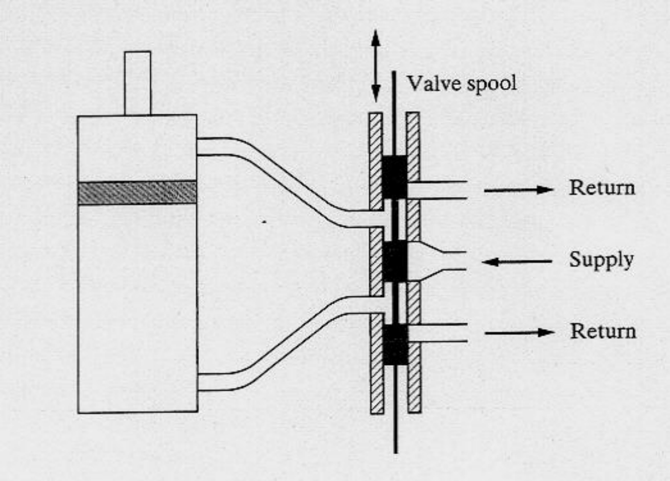
1. **Hydraulic linear or rotary cylinders and rams** to provide the force or torque needed to move the joints and are controlled by servo valve or manual valve.
2. **A hydraulic pump** to provide high pressure fluid to the system
3. **Electric motor** to operate the hydraulic pump.
4. **Cooling system** to get rid of heat (cooling fans, radiators, and cooled air).
5. **Reservoir** to keep fluid supply available to the system.
6. **Servo valve** which is a very sensitive valve that controls the amount and the rate of the fluid to the cylinders. The servo valve is generally driven by a hydraulic servomotor.
7. **Sensors** to control the motion of the cylinders (position, velocity, magnetic, touch,..)
8. **Connecting hoses** to transport the pressurized fluid.
9. **Safety check valves, holding valves**.



Electrohydraulic and electromechanical actuators.

Hydraulic Actuators

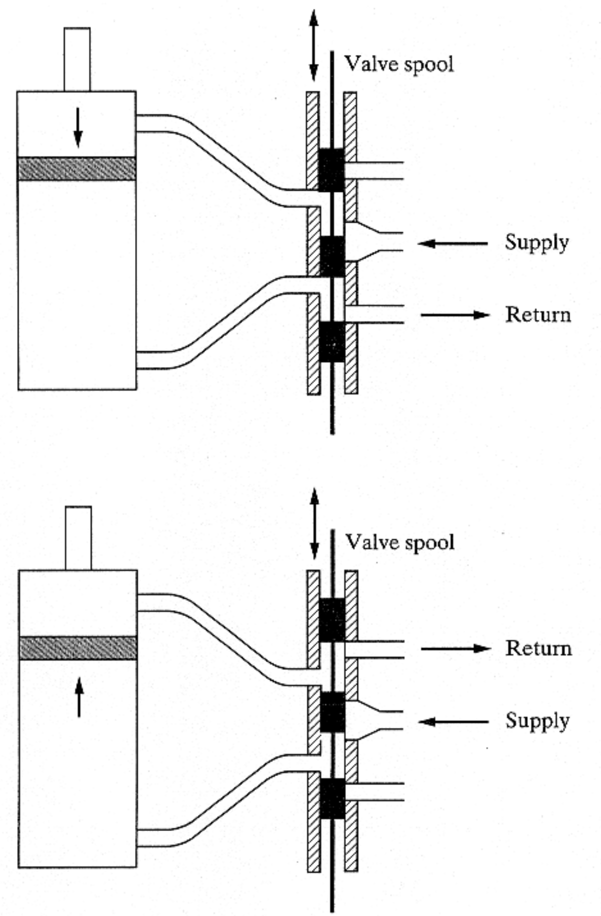
- **Spool Valve**
- Spool valve or pilot valve is a balanced valve, which means that the pressure on the two sides of the spool is equal so a little force can move it, even though it may be under high pressure.
- When a servomotor is attached to the spool valve to operate it, a servo valve is created. The servo valve and the cylinder together form a hydraulic servomotor.
- As the spool moves up and down, it opens the supply and return ports through which the fluid travels to the cylinders or is returned to the reservoir.
- Velocity of the cylinder can be controlled based on the size of the opening of the port.
- The total travel of the cylinder is controlled based on the length of the time that the port is kept open.



Schematic diagram of a spool valve in neutral position

Hydraulic Actuators

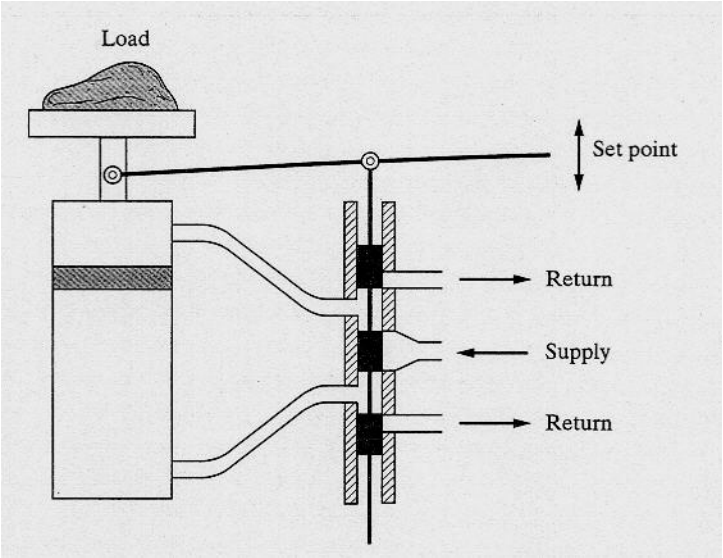
- The controller sets the current to the servomotor, as well as the duration the current is applied, to control the position of the spool. The controlling procedure is as follows:
  - Position and velocity should be calculated by the controller.
  - Set the amount of current and its duration to the servomotor.
  - Controlling the position and rate of movement of the spool valve.
  - Controlling the flow and its rate to the cylinder.
  - The cylinder moves the joint.
  - The sensors provide feedback to the controller for accurate and continued control.

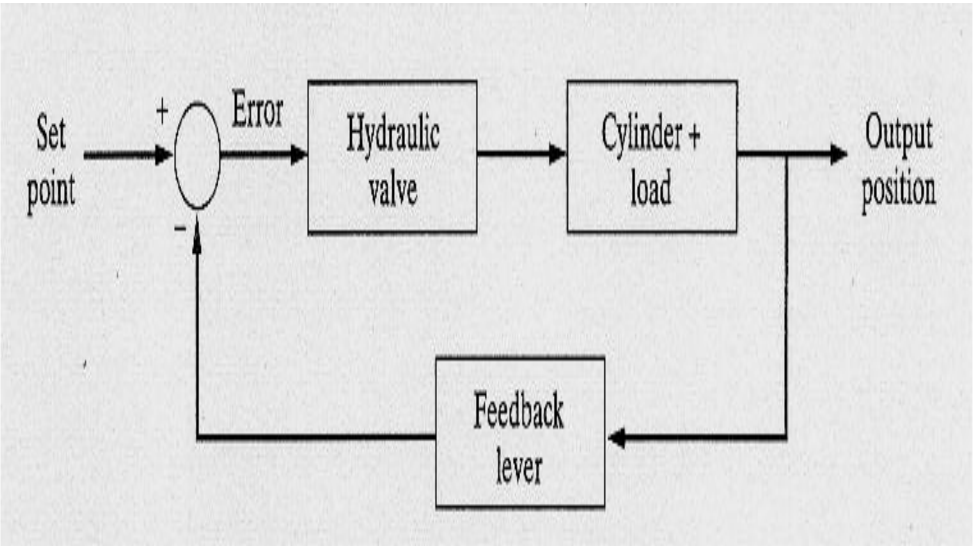


Schematic diagram of a spool valve in open position. Depending on which ports is open, the direction of motion of the piston will change

Hydraulic Actuators

- **Mechanical Feedback Strategy**
- As the desired position for the load is set by the set point lever, say up, the spool valve is opened which will operate the cylinder. This will provide error signal (fluid pressure) to the cylinder.
- The error signal is integrated by the integrator and the error approaches zero.





Schematic diagram of a simple control device with proportional feedback