Manipulator Design

We now have seen much of what is required to introduce a robot manipulator into a work environment

- Forward and inverse kinematics
- Velocity and static force analysis
- Dynamical analysis

The design of the robot mechanism critically affects how straight forward this analysis will be.

For example we saw that some manipulators will have inverse kinematics expressible in closed form, while others will not

Also, to this point we have simply assumed that joints will actuate and sensing information will be available without investigating the details of how this is done.

Divide our presentation into 3 parts:

- Mechanism (arm) design
- Actuator system (motors, transmissions, etc)
- Sensor system

Mechanism Design

Mechanism must be designed with the end task in mind.

Robots are general purpose "universally programmable" machines, but to a point.

A robot designed for welding or carrying heavy loads will not generally be ideal for carrying out keyhole surgery or for placing electronic components

A number of design decisions need to be made

- degrees of freedom (dof)
- workspace extent

- load carrying capacity
- end effector maximum speed
- repeatability and accuracy

Degrees of Freedom

Six dof the minimum required to achieve any position in any pose.

A common strategy in design is to put a 3-dof base to achieve arbitrary position, and add a 3-dof spherical wrist to achieve arbitrary orientation, eg. Puma, Stanford Arm.

Often manipulators made 5-dof due to assumption of symmetric tool piece.

Many of the common tasks completed by robots are symmetric around the tool piece (welding, spray painting, etc), so 5-dof robots are quite common - eg. scorbot.

Often the task at hand does not require a full 6-dof, eg. when task objects exhibit symmetry, or when no "obstacles" in workspace, or simply when the task involves limited directions of movement (eg. placing pcb components is planar).

Obviously we want to design the manipulator with the minimum dof that will achieve the task. This reduces cost and simplifies the analysis.

Other manipulator properties

Workspace: The reachable and dexterous workspace will depend on the task. A fruit picking robot will obviously require a larger workspace than a electronic component placement or medical robot.

Sometimes the "shape" of the workspace needs to be considered.

Load capacity: The load required to be carried by the robot will govern the size of its motors, and the structural integrity of its joints and links.

For the same level of structural integrity, the payload capacity will decrease as the workspace volume increases.

Speed: the faster a task can be achieved, the more viable is the robot compared to hard automation or human workers.

Cycle time, the time taken to achieve a complete move, is a function end effector speed, but also on the accelerations possible during the acceleration and deceleration phases. So acceleration capability is also of importance.

Repeatability and Accuracy: This is one of the critical properties of any robot. Constructing a robot with high accuracy and repeatability is expensive: stiffer links, tighter tolerance joints, position sensing, and modelling, etc.

Should aim for the minimum accuracy and repeatability required by the task.

External sensing, particularly force sensing, is a means in many tasks to reduce the required level or accuracy. This has been and still is a current active research area.

Kinematic Configuration

Often a manipulator is designed so that the first three joints are "decoupled" from the last three. The first three joints provide arbitrary position, and the last three an arbitrary orientation (we mentioned this before).

This approach has the advantage that any manipulator designed in this form is guaranteed to have a closed form solution for the inverse kinematics.

This form of kinematic chain is used in almost all the common industrial robots today.

There are a number of popular standard robot configurations for the first three joints.

- Cartesian
- Anthropomorphic
- SCARA
- Spherical
- Cylindrical

A *Cartesian* manipulator consists of all prismatic joints. Prismatic joints can generally be made quite strong, so large gantry type robots are used to move cars or aircraft.

Other advantages are that forward and inverse kinematics calculations for these joints are straightforward. The disadvantage is that feeders and fixtures must lie "inside" the robot, and so are quite specific to the robot. Difficult to retrofit Cartesian manipulator into existing set up.

An *Anthropomorphic* robot consists of all revolute joints and mirrors the human form (ie. the origin of the anthropomorphic term) with a shoulder, elbow and wrist. Eg. Puma and scorbot robots.

Main advantage is that they intrude very little into the workspace since they require little overall structure, allowing confined places to be reached. Less structure also means less expensive.

A *SCARA* robot consists of three parallel revolute joints allowing position and orientation in the horizontal plane, with a prismatic joint to achieve height.

Main advantages are that motors of first three joints don't have to support weight, and that joints 2 and 3 can be driven from the robot base, reducing moving mass. Result is a very fast end effector movement (10 times faster than the anthropomorphic design at around 10 m/s).

Best suited to planar or "almost" planar tasks, eg. pick and place in the horizontal plane; a common task.

A *spherical* robot consists of two revolute joints with a final prismatic joint. The manipulator essentially physically implements the idea of spherical coordinates. One of the earliest designed manipulator, the Stanford Arm, was of this type.

A *cylindrical* robot has a RPR joint configuration. Implements the idea behind cylindrical coordinates.

Wrists

The wrist is usually designed to achieve arbitrary orientation. Usually consist of two or three revolute joints with orthogonal and intersecting axes.

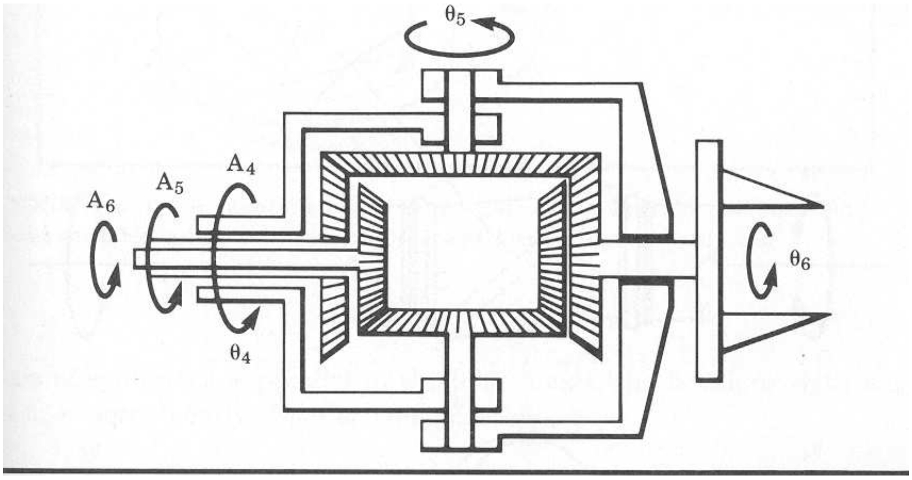
Most common is the spherical wrist found on the Puma and Stanford Arm, etc.

Three intersecting joint axes guarantee a closed form inverse kinematics solution.

Also has the advantage that all joints can be driven from the base of the mechanism, although joint limits can be restrictive.

For 5-dof robots with symmetric tool pieces, a 2 joint wrist is usually mounted on the 3 joint base. The wrist usually consists of two revolute joints, the first perpendicular to the direction of the arm, the second along its axis (eg. the Scorbot).

To achieve arbitrary orientation, given the tool is symmetric, the symmetry of the tool must be perpendicular to joint 5. When the symmetry is parallel, the robot is permanently in a singular configuration

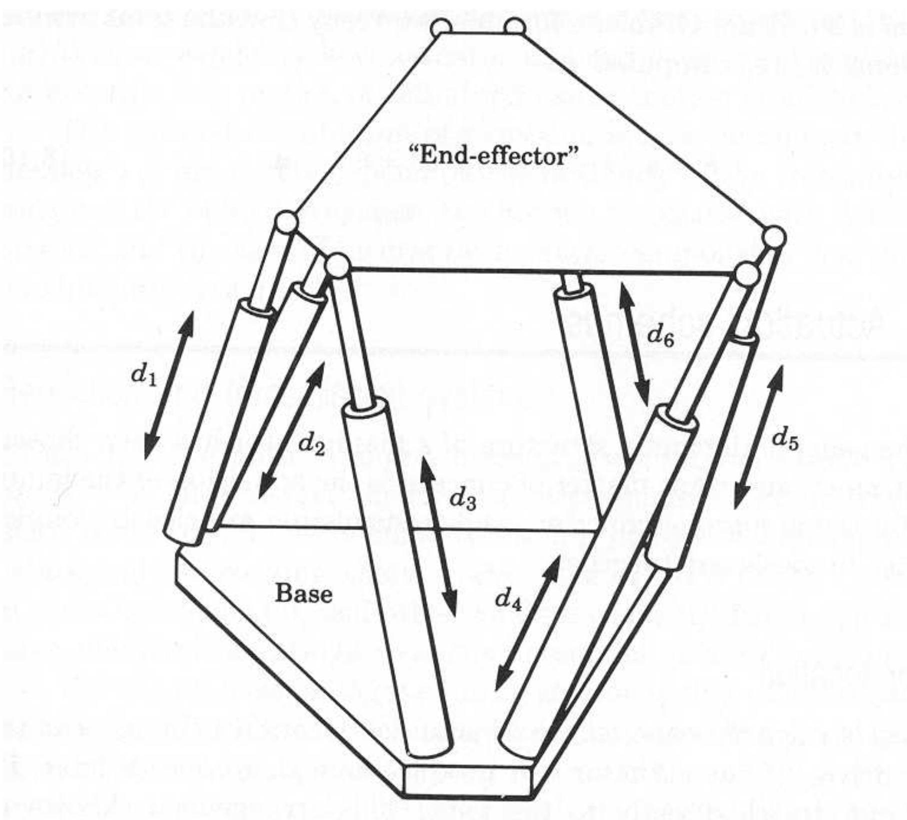


This latter case is in fact the situation in the Scorbot lab, but it does not cause a problem because the dof of the writing task is less than the dof of scorbot in this singular configuration.

Closed Loop Structures

An alternative type of robotic mechanism to serial manipulators are parallel actuated manipulators

The Stewart platform is the most well known of these. It has six actuators mounted in such a way as to give a platform with 6 dof.



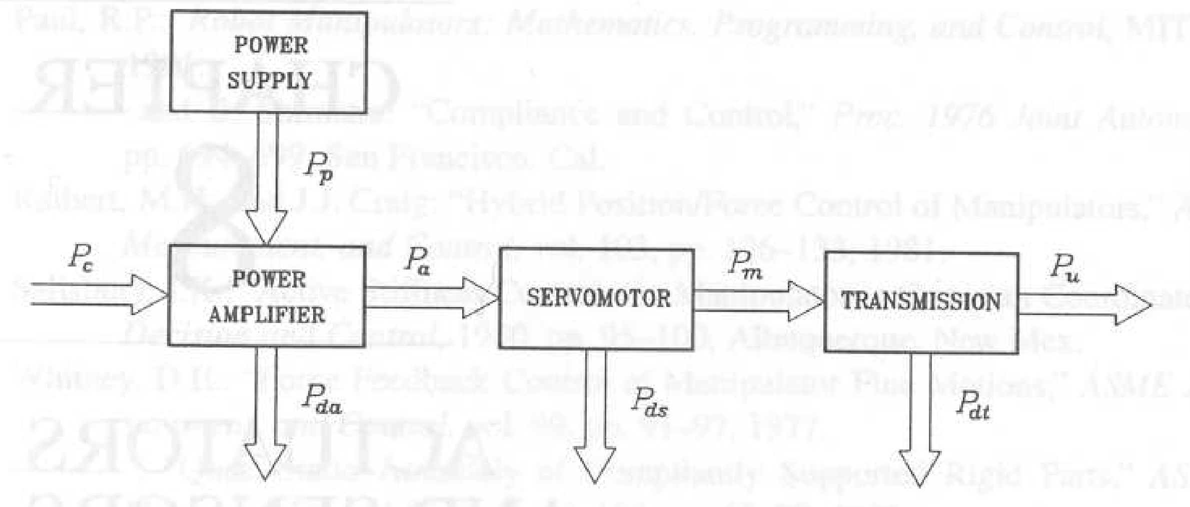
Closed loop structures like the Stewart platform have the advantage that they are very rigid, and can provide precise movement of the end effector.

The disadvantage of these mechanisms is that their range of motion is limited.

One application that I have seen this type of mechanism is as a workpiece platform for an automatic milling machine.

Actuation System

The actuation system can be represented schematically as



A power supply provides energy to a power amplifier, which takes the required amount of energy to feed to the motor depending on the control signal.

The powered motor then drives the joint through a transmission.

P_{da}, P_{ds}, P_{dt} each represent power losses

Choose the components in order from the joint back. The specifications of each component depend on the requirements of the component one step further down the line.

Transmissions

Joint motion generally requires low speed and high torque, whereas electric motors supply high speed and low torque at optimum operating states.

Results in the need for a "transmission" supplying mechanical advantage.

In some cases, another role of a transmission is to transmit to the joint from a motor mounted in the base of the robot, reducing moving mass.

Options for transmission methods in a traditional gearbox are *spur gears* and *lead screws*. Both suffer from backlash and friction.

Timing belts and chains are the same kinematically, however they allow the motor to be located remote of the joint. Backlash still a significant problem, and friction to a lesser degree. Vibration at high speed also a problem with chains, and belts only generally can transmit low torques

A more recent method of transmission is using a *cable drive*. Disadvantage is that infinite rotation not possible; but this is not required for a joint with limited rotation.

Advantages of cable drive is zero backlash and very low friction.

Servo motors

Actuation through transmission of joints is by motors.

A servomotor is one where some sort of position sensor is part of the motor unit, and there is an internal control loop which allows precise positioning of the motor.

- Pneumatic Motors: use compressed air from a compressor to produce motion via pistons or turbines
- Hydraulic Motors: use compressed fluid (oil) stored in a reservoir to produce motion via pumps
- Electric Motors: most common, electrical energy from distribution system produce motion using magnetic fields.

Requirements on motor for robotic application

- low inertia and high power to weight ratio
- possibility of short term overload and delivery of impulse torques
- capacity to develop high accelerations
- wide velocity range
- high positioning accuracy
- low torque ripple - smooth rotation even at low speeds

Pneumatic motors difficult to control due to air compressibility. Used in“binary” application like for opening or closing a gripper

Electric and hydraulic motor both suitable for robotic application

The advantages of hydraulic motors

- they do not burn out in static situations
- they are self lubricating, and circulating fluid assists heat disposal
- safe - no high voltage or sparks
- excellent power to weight ratios

However their disadvantages are:

- need a hydraulic power station
- are expensive, with narrow product range
- low power conversion efficiency
- maintenance intensive
- pollution and messy due to oil leakage

Electric motors are the most popular type of robotic actuation technology

Their advantages are:

- wide spread availability of electrical power
- low cost and wide range of products
- high power conversion efficiency
- easy maintenance
- no pollution of work environment

Many types of electric servomotor. The most popular are DC permanent magnet and brushless dc servo motors.

A permanent magnet dc servomotor is made up of

- A stator coil that generates magnetic flux - always a set of permanent magnets - high field strength eg. rare earth magnets

- An armature that is a current carrying winding on rotor with ferromagnetic core.
- a commutator that connects the rotor to the fixed power supply, with commutation logic determined by the rotor motion.

A brushless dc servomotor is made up of

- A rotor made up of permanent magnets
- A stationary armature made up of a polyphase winding
- a static commutator, ie. on the basis of a position sensor on the motor shaft (eg. a hall effect sensor) commutation control circuitry provides the correct feed sequence of armature winding phases.

Brushless dc servomotor has a number of advantages

- extra resistance due to contact of mechanical commutation limits maximum performance of permanent magnet dc motors, eg. problems with sparking etc. No issue with brushless.
- winding on the stator instead of the rotor means better heat dissipation since closer to outside casing - therefore increased maximum ratings.
- rotor as permanent magnet construction generally leads to a rotor with lower rotational inertia - better performance, and smaller size of overall motor.

The disadvantage of the brushless dc servomotor is that its commutation requires more (ie. some) complex control circuitry, that historically was technically difficult and therefore expensive. These days, this is no more a problem

Power Amplifiers and Power supply

The power supply is simply a unit which converts electrical energy into a form (usually DC) and a voltage that is suitable for input into the power amplifier units.

Power supplies are usually made up of a transformer to convert to an appropriate voltage, and then a bridge rectifier circuit to convert it to DC.

The power amplifier has the task of modulating the amount of electrical power extracted from the power supply that is delivered to a motor.

The quantity of power transferred will by controlled by the control signal into the amplifier from the computer or control device.

Since motors on a robot need to be controlled separately, there will be one power amplifier for each joint (motor) of the robot.

Sensors

Robotic sensors can be broadly split into two types:

- proprioceptive sensors: measurement of robots internal state
- heteroceptive sensors: measurement of state of surrounding environment

Proprioceptive Sensors

There are 3 elements of most interest in the measurement of internal robot state:

- joint position
- joint velocity
- forces acting on the mechanical structure

Position transducers

Position transducers come in forms allowing measurement of both linear and angular position.

The types of technologies used for linear transducers are potentiometers, inductosyns, magnetostrictive devices, linear optical encoders.

For angular displacement the main technologies include potentiometers, optical encoders, resolvers, and syncros.

Revolute joints are the main type utilised in manipulators, hence rotary displacement transducers are most used in robotics (linear transducers are more utilised in machine tools). The two main types used are encoders and resolvers.

Encoders and Resolvers

Encoders work by passing a light beam through a transparent disk that has had metal film deposited in various sectors so that light cannot pass through the disk at these points.

Absolute encoders have the disk divided into n concentric rings, where n is the resolution of the encoder. Each sector then has a binary number "written into it" by blacking out the appropriate spaces in the sector. To divide a full revolution into 4096 positions, one requires $n = 12$.

Incremental encoders at most consist of 3 concentric rings. Two of the tracks provide simple square wave signals that are in quadrature. They allow determination of the amount and direction of rotation. By summing this information to get relative position, and knowing an absolute position on the encoder (an index pulse provided by the third track), we can know our absolute position.

Resolvers are electromechanical position sensing devices that consist of a rotor and stator. The stator has two windings, each at $90°$ to one another. Each is driven by a sinusoidal voltage signal. The rotor is an inductance coil, that has a voltage signal induced in it from the stators. The precise position of the rotor wrt to the stators can be determined by this signal.

Velocity transducers

Even though velocity measurements can be made by differentiating position transducer measurements, often it is preferred to directly measure it. Rotational velocity transducers are called "tachometers" and are widely used in robots and other hard automation.

Two main types, dc tachometers and ac tachometers.

dc tachos are basically small dc generators whose magnetic field is provided by a permanent magnet. The idea is that angular velocity of the shaft causes a dc voltage on the output terminals. Every effort is made to construct the device so that the output voltage is linear wrt angular velocity which is independent of magnetic hysteresis and temperature.

One of the disadvantage of the dc tacho is a residual ripple on the output signal because of the mechanical commutation, ac tachos are an option, ie. where no commutation is included.

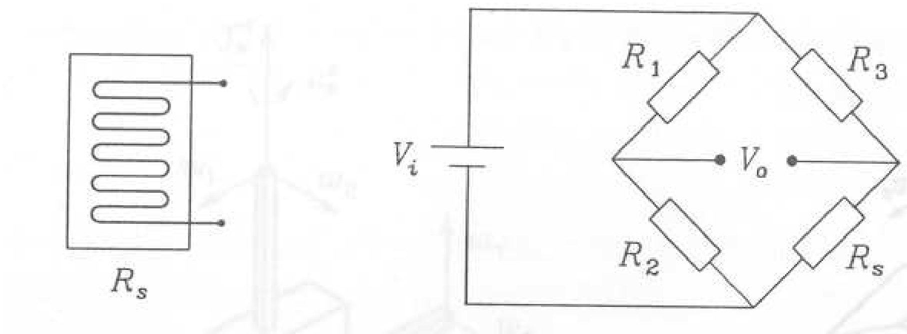
AC tacho has two winding in quadrature in the stator and a simple cup rotor. One of the windings is fed a sinusoidal signal which appears via the cup rotor on the other, with magnitude proportional to the angular speed of the rotor.

Force Sensors

Force and torque measured by measuring deflection using a strain gauge.

Strain gauge consists of resistance wire mounted on an insulated substrate fixed to the element under strain

Change in length of the resistance wire due to strain changes its resistance



Resistance wire is interfaced electronically by making it one leg of the usual wheatstone bridge circuit.

For robotic applications, strain gauges mounted on a deflectable "flexure" structure in the manipulator chain

Design issues relevant to this structure include

- overload protection essential. Damage can be avoided by introducing limit stops to stop strain beyond elastic limit
- difficult to build limit stops accurately enough if typical strain is small, Flexures need to be sufficiently flexible
- Can increase the sensitivity of the device by strategically placing 2 resistance wires so that one experiences compression and the other tension
- hysteresis can be a problem. Usually caused by bolted, press-fit or welded joints in flexures. Minimise hysteresis by manufacturing flexures from a single piece of metal.

For robotics applications, where the force sensor is mounted at the wrist, the flexure structure is usually a "Maltese cross"

Usually the force sensor is mounted between the final robot link and the end effector or tool. Gives readings in sensor frame. Need to transform to be in workpiece contact point frame.

Can only measure contact forces applied to the end effector or tool

Tactile sensors are an advanced form of force sensing since they give a reading of force distributed over a range of positions, although the force reading is usually only in the direction normal to the surface.

Difficult to build due to large number of sensors in small proximity - cabling problems, etc. Still a research area.

One of the new ideas behind the wam arm was to remove the use of gearbox transmissions and use cable drives (reduce friction) so that force sensing can be achieved by monitoring motor torque. This lifts the restriction that force applied to the robot can only be sensed if downstream of force sensor.

Heteroceptive Sensors

Recall that devices gathering information *external* to the robot are called heteroceptive sensors.

For a robot manipulator the most common one is vision sensing.

Two basic types of set-ups: Cameras mounted "in hand", or in the environment.

In industrial settings, cameras mounted in the environment above a conveyor belt can be used to find where a part on the belt is. Vision algorthims are used to find appropriate features - maybe where to grasp. Structured lighting often used.

The other approach is to have the camera mounted in the hand. In essence we can modify what is in the camera frame by moving the hand.

With both approaches, in many instances the idea is to use the camera information for control of the robot. This is called visual servoing.

For manipulators, type of heteroceptive sensor used in practice limited because the robot fixed, the same local environment.

For mobile robots, a wider array of heteroceptive sensors are used

- laser range finders
- vision (stereo) (panoramic)
- sonar sensors
- infra-red sensors
- wheel encoders
- bump sensors