UNIT III – GRIPPERS AND ROBOT DYNAMICS

Introduction - various types of grippers-design considerations. Construction of Manipulator – Introduction to Robot Dynamics – Lagrange formulation – Newton Euler formulation – Properties of robot dynamic equations

Introduction

In robotics, an end-effector is the device at the end of a robotic arm, designed to interact with the environment. The exact nature of this device depends on the application of the robot.

In the strict definition, which originates from serial robotic manipulators, the end effector means the last link (or end) of the robot. At this endpoint the tools are attached. In a wider sense, an end effector can be seen as the part of a robot that interacts with the work environment. This does not refer to the wheels of a mobile robot or the feet of a humanoid robot which are also not end effectors—they are part of the robot's mobility

Considerations in robot gripper selection and design

The industrial robots use *grippers* as an end effector for picking up the raw and finished work parts. A robot can perform good grasping of objects only when it obtains a proper gripper selection and design. Therefore, *Joseph F. Engelberger*, who is referred as *Father of Robotics*has described several factors that are required to be considered in gripper selection and design.

- The gripper must have the ability to *reach* the surface of a work part.
- The change in work part size must be *accounted* for providing accurate positioning.
- During machining operations, there will be a change in the work part size. As a result, the gripper must be *designed* to hold a work part even when the size is *varied*.
- The gripper must not create any sort of *distort* and *scratch* in the fragile work parts.
- The gripper must hold the *larger area* of a work part if it has various dimensions, which will certainly increase *stability* and *control* in positioning.
- The gripper can be designed with *resilient pads* to provide more grasping contacts in the work part. The *replaceable fingers* can also be employed for holding different work part sizes by its *interchangeability* facility.

Moreover, it is difficult to find out the *magnitude of gripping force* that a gripper must apply to pick up a work part. The *following significant factors* must be considered to determine the necessary gripping force.

- Consideration must be taken to the *weight* of a work part.
- It must be capable of grasping the work parts constantly at its *center of mass*.

- The *speed* of robot arm movement and the connection between the direction of movement and gripper position on the work part should be *considered*.
- It must determine either *friction* or *physical constriction* helps to grip the work part.
- It must consider the *co-efficient of friction* between the gripper and work part

<u>Various types of artificial gripper mechanisms</u>

Gripper mechanisms can be classified into the following major categories:

1) Mechanical finger grippers – sub classification is based on method of actuation.
2) Vacuum and magnetic grippers – sub-classification is based on type of the force-exerting elements.
3) Universal grippers – sub-classification is inflatable fingers, soft fingers & three fingered grippers.
4) Adhesive grippers
5) Hooks, scoops

<u>Mechanical finger grippers</u>

(a) Linkage grippers: there is no cam, screw, gear. There is movement only because of links because of links attached to input and output. There must be perfect design of mechanism such that input actuator's motion is transformed into the gripping action at the output.

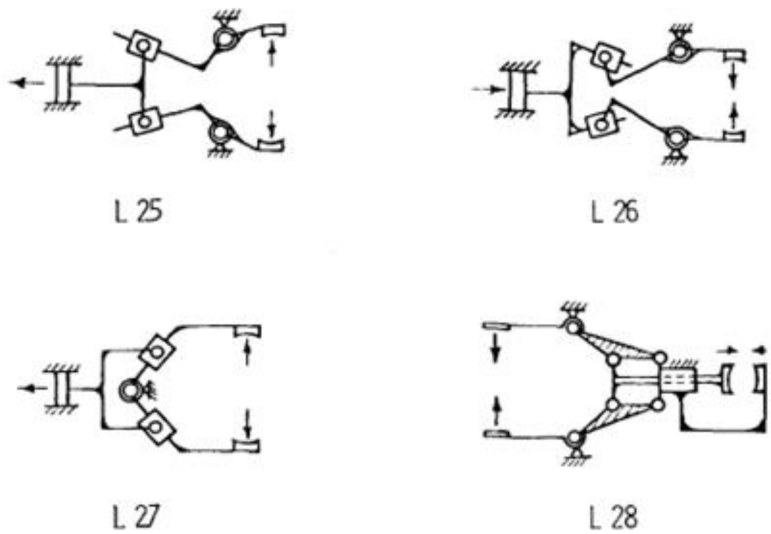


Fig 3.1: Linkage Grippers

Gear and Rack Grippers: movement of input due to gear motion which makes connecting links to go in motion to make gripping action at the output link.

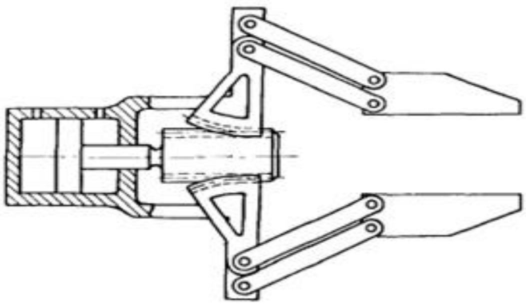


Fig 3.2: Gear and Rack Grippers

Cam-actuated Grippers:

Reciprocating motion of the cam imparts motion to the follower, thus causing fingers toproduce a grabbing action. A variety of cam profiles can be employed- constant velocity, circular arcs, harmonic curves etc.

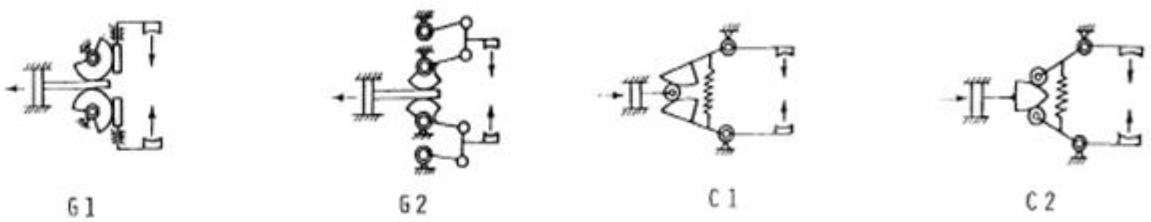


Fig 3.3 Cam-actuated Grippers

Screw-driven Grippers:

Operated by turning screw, in turn giving motion to connecting links and thus giving griping motion to output. Screw motion can be controlled by motor attached.

Fig 3.4: Screw-driven Grippers

Rope & Pulley Grippers:

Motor attached to the pulley makes the winding and unwinding motion of rope in turn it set gripper action into motion via connecting link.

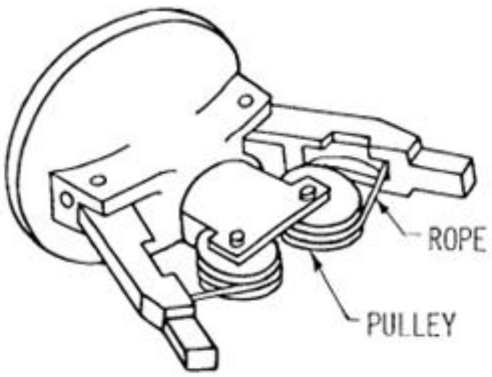


Fig 3.5: Rope & Pulley Grippers

Vacuum & Magnetic Grippers

Vacuum Grippers:

For non-ferrous components with flat and smooth surfaces, grippers can be built using standard vacuum cups or pads made of rubber-like materials. Not suitable for components with curved surfaces or with holes.

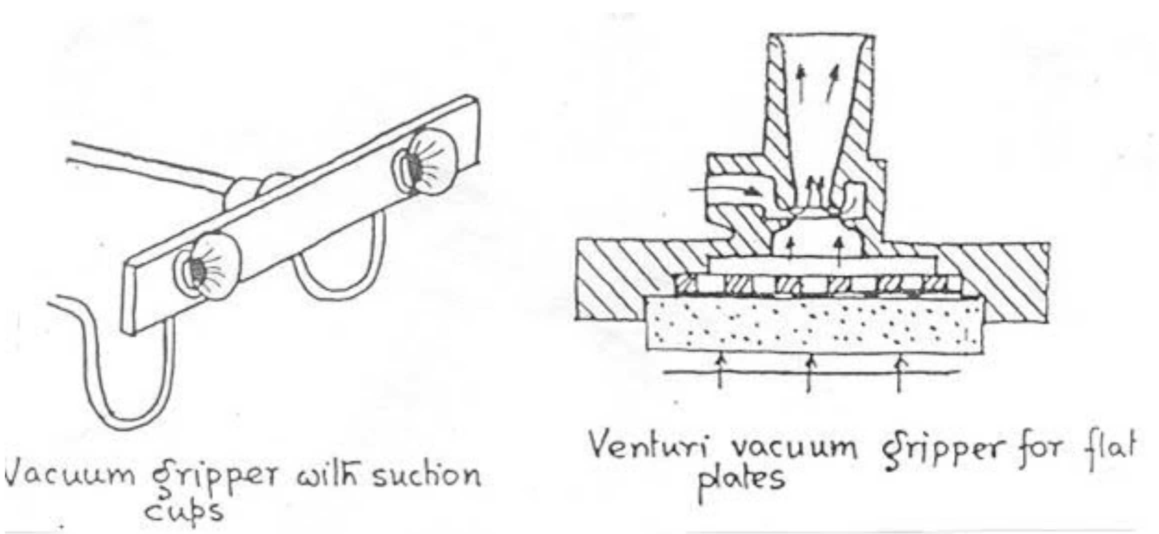
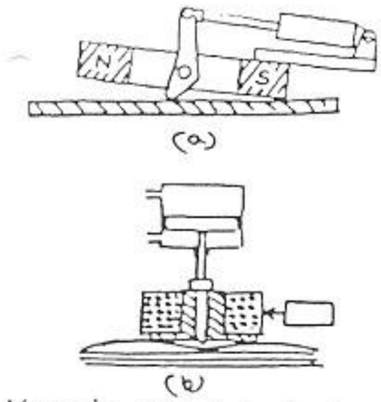


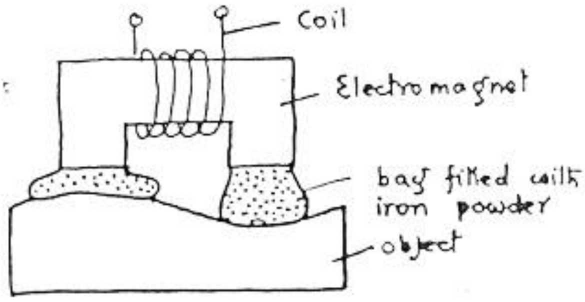
Fig 3.6: Vacuum Grippers

Magnetic Gripper:

It is used to grip ferrous materials. Magnetic gripper uses a magnetic head to attract ferrous materials like steel plates. The magnetic head is simply constructed with a ferromagnetic core and conducting coils.



Magnetic gripping device with (a) release mechanism and (b) a system to prevent more than one object to be picked up.



Form-adaptable magnetic gripper

Fig 3.7: Magnetic Grippers

<u>**Versatile or universal Grippers**</u>

Inflatable grippers

It is used for picking up irregular and fragile objects without concentrated loading. In the initial position before gripping, the lever 1, are opened up, the bellows are in a compressed condition because the gas pressure in the bags,3, with the spheres is close, even ah slight pressure of the object on a bag is sufficient enough to cause the bag wall to be deeply depressed and surround the object. When the degree of the surrounding is adequate the lever motion ceases, and pressure in the bags is reduced by bellows, diaphragm device or vacuum pump, causing bags to harden without changing shape and hence gripping the object. To release the object operation is done in reverse.

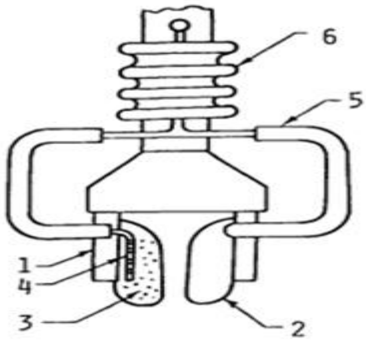


Fig 3.8: Inflatable Grippers

Soft Grippers:

It consists of multi-links and a series of pulleys actuated by a pair of wires. The soft gripper can actively conform to the periphery of objects of any shape and hold them with uniform pressure.

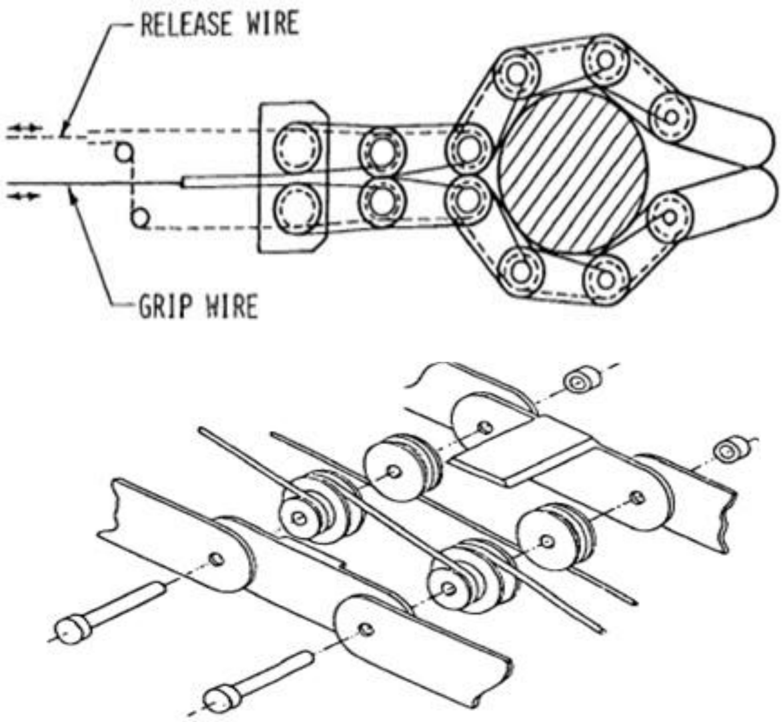


Fig 3.9: Soft Grippers

Three Fingered Grippers:

The clamping movement of two-fingered type normally executes

(a) beat movement
(b) bite movement
(c) Parallel movement of the jaw.

They are capable only of grasping or releasing movement.

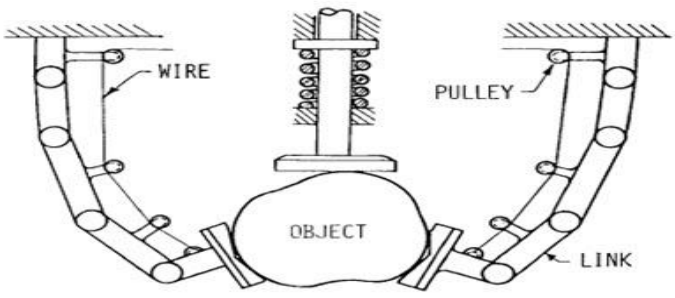


Fig 3.10: Three Fingered Grippers

Adhesive grippers

An adhesive substance can be used for grasping action in gripping design. The requirements on the items to be handled are that they must be gripped on one side only. The reliability of this gripping device is diminished with each successive operation cycle as the adhesive substance loses its tackiness on repeated use. To overcome this limitation, the adhesive material can be loaded in the form of a continuous ribbon into a feeding mechanism attached to the robot wrist.

Hooks, scoops

Hooks can be used as end-effectors to handle containers and to load and unload parts hanging from overhead conveyors. The item to be handled by a hook must have some sort of handle to enable the hook to hold it.

Ladles and scoops can be used to handle certain materials in liquid or powder form. One of the limitations is that the amount of material being scooped by the robot is sometimes difficult to control.

Introduction to manipulators

Industry-specific robots perform several tasks such as picking and placing objects, movement adapted from observing how similar manual tasks are handled by a fully-functioning human arm. Such robotic arms are also known as robotic manipulators. These manipulators were originally used for applications with respect to bio-hazardous or radioactive materials or for use in inaccessible places.

A series of sliding or jointed segments are put together to form an arm-like manipulator that is capable of automatically moving objects within a given number of degrees of freedom. Every commercial robot manipulator includes a controller and a manipulator arm. The performance of the manipulator depends on its speed, payload weight and precision. However, the reach of its end-effectors, the overall working space and the orientation of the work is determined by the structure of the manipulator.

Kinematics of a Robotic Manipulator

A robot manipulator is constructed using rigid links connected by joints with one fixed end and one free end to perform a given task (e.g., to move a box from one location to the next). The joints to this robotic manipulator are the movable components, which enables relative motion between the adjoining links. There are also two linear joints to this robotic manipulator that ensure non-rotational motion between the links, and three rotary type joints that ensure relative rotational motion between the adjacent links.

The manipulator can be divided into two parts, each having different functions:

Arm and Body – The arm and body of the robot consists of three joints connected together by large links. They can be used to move and place objects or tools within the work space.

Wrist – The function of the wrist is to arrange the objects or tools at the work space. The structural characteristic of the robotic wrist includes two or three compact joints.

Robotic Manipulator Arm Configuration

Manipulators are grouped into several types based on the combination of joints, which are as follows:

- Cartesian geometry arm – This arm employs prismatic joints to reach any position within its rectangular workspace by using Cartesian motions of the links.
- Cylindrical geometry arm – This arm is formed by the replacement of the waist joint of the Cartesian arm with a revolute joint. It can be extended to any point within its cylindrical workspace by using a combination of translation and rotation.
- Polar/spherical geometry arm – When a shoulder joint of the Cartesian arm is replaced by a revolute joint, a polar geometry arm is formed. The positions of end-effectors of this arm are described using polar coordinates.
- Articulated/revolute geometry arm - Replacing the elbow joint of the Cartesian arm with the revolute joint forms an articulated arm that works in a complex thick-walled spherical shell.
- Selective compliance automatic robot arm (SCARA) – This arm has two revolute joints in a horizontal plane, which allow the arm to extend within a horizontal planar workspace. The TH650A SCARA Robot by TM Robotics is a great example to demonstrate pick and place functionality of robotic manipulators

Introduction to robot dynamics

While Kinematics deals with finding position, velocity & acceleration based on geometrical constraints, dynamics is concerned with solving for these when an external force acts on the system or the system is released to evolve from some initial position (e.g. Pendulum).

Now we will consider some simple examples to make clear understanding of dynamics.Consider a block sliding on the frictionless floor. A force of constant magnitude F is applied to block. Dynamical equation can be easily found out in this case. Basically dynamical equations are mathematical model governing dynamic behavior of system. These equations are the force-mass-acceleration or the torque-inertia-angular acceleration relationships. By knowing the magnitude of applied force & mass of block, velocity & acceleration can be easily found out at every instant of time if we know initial conditions such as whether body is at rest or moving with certain velocity.

In this portion, we analyze the dynamic behavior of robot mechanisms. The dynamic behavior is described in terms of the time rate of change of the robot configuration in relation to the joint torques exerted by the actuators. This relationship can be expressed by a set of differential equations, called *equations of motion,* that govern the dynamic response of the robot linkage to input joint torques. In the next chapter, we will design a control system on the basis of these equations of motion.

Two methods can be used in order to obtain the equations of motion: the *Newton-Euler formulation,* and the *Lagrangian formulation.* The Newton-Euler formulation is derived by the direct interpretation of Newton's Second Law of Motion, which describes dynamic systems in terms of force and momentum. The equations incorporate all the forces and moments acting on the individual robot links, including the coupling forces and moments between the links. The equations obtained from the Newton-Euler method include the constraint forces acting between adjacent links. Thus, additional arithmetic operations are required to eliminate these terms and obtain explicit relations between the joint torques and the resultant motion in terms of joint displacements. In the Lagrangian formulation, on the other hand, the system's dynamic behavior is described in terms of work and energy using generalized coordinates. This approach is the extension of the indirect method discussed in the previous chapter to dynamics. Therefore, all the workless forces and constraint forces are automatically eliminated in this method. The resultant equations are generally compact and provide a closed-form expression in terms of joint torques and joint displacements. Furthermore, the derivation is simpler and more systematic than in the Newton-Euler method.

The robot's equations of motion are basically a description of the relationship between the input joint torques and the output motion, i.e. the motion of the robot linkage. As in kinematics and in statics, we need to solve the inverse problem of finding the necessary input torques to obtain a desired output motion. This *inverse dynamics* problem is discussed in the last section of this chapter. Efficient algorithms have been developed that allow the dynamic computations to be carried out on-line in real time.

Newton-Euler Formulation of Equations of Motion

Basic Dynamic Equations

In this section we derive the equations of motion for an individual link based on the direct method, i.e. Newton-Euler Formulation. The motion of a rigid body can be decomposed into the translational motion with respect to an arbitrary point fixed to the rigid body, and the rotational motion of the rigid body about that point. The dynamic equations of a rigid body can also be represented by two equations: one describes the translational motion of the centroid (or center of mass), while the other describes the rotational motion about the centroid. The former is Newton's equation of motion for a mass particle, and the latter is called Euler's equation of motion.

Dynamic Analysis and Forces

<u>TRANSFORMATION OF FORCES AND MOMENTS BETWEEN COORDINATE FRAMES</u>

Displacements relative to the two frames are related to each other by the following relationship.

$$\left[{}^{B}D\right]=\left[{}^{B}J\right]\left[D\right]$$

The forces and moments with respect to frame B is can be calculated directly from the following equations:

$$\begin{aligned}
{}^{B}f_x &= \overline{n}\cdot\bar{f} \qquad & {}^{B}m_x &= \overline{n}\cdot[(\bar{f}\times\overline{p})+\overline{m}]\\
{}^{B}f_y &= \overline{o}\cdot\bar{f} \qquad & {}^{B}m_y &= \overline{o}\cdot[(\bar{f}\times\overline{p})+\overline{m}]\\
{}^{B}f_y &= \overline{o}\cdot\bar{f} \qquad & {}^{B}m_z &= \overline{a}\cdot[(\bar{f}\times\overline{p})+\overline{m}]
\end{aligned}$$

<u>LAGRANGIAN MECHANICS:</u>

<u>A SHORT OVERVIEW</u>

Lagrangian mechanics is based on the differentiation energy terms only, with respect to the system's variables and time.

Definition: L = Lagrangian, K = Kinetic Energy of the system, P = Potential Energy, F = the summation of all external forces for a linear motion, T = the summation of all torques in a rotational motion, x = System variables

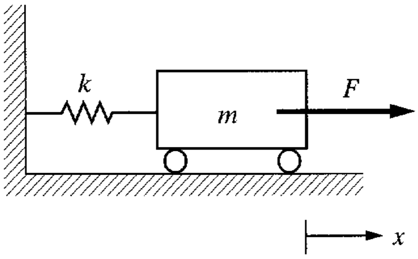
$$L = K - P$$

$$F_i = \frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{x}_i}\right) - \frac{\partial L}{\partial x_i}$$

$$T_i = \frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \frac{\partial L}{\partial \theta_i}$$

Derive the force-acceleration relationship for the one-degree of freedom system.

The appropriate form of the dynamic equations therefore consists of equations described in terms of all independent position variables and input forces, i.e., joint torques, that are explicitly involved in the dynamic equations. Dynamic equations in such an explicit input- output form are referred to as *closed-form dynamic equations.* As discussed in the previous chapter, joint displacements **q** are a complete and independent set of generalized coordinates that locate the whole robot mechanism, and joint torques are a set of independent inputs that are separated from constraint forces and moments. Hence, dynamic equations in terms of joint displacements **q** and joint torques are closed-form dynamic equations.



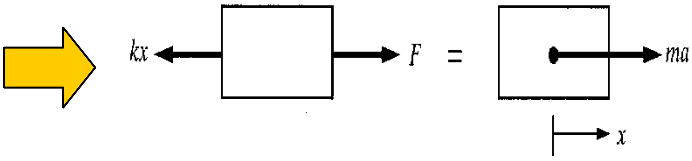


Fig. 3.11 Schematic of a simple cart-spring system

Fig. 3.12 Free-body diagram for the sprint-cart system

$$K = \frac{1}{2}mv^2 = \frac{1}{2}m\dot{x}^2, P = \frac{1}{2}kx^2 \Rightarrow L = K - P = \frac{1}{2}m\dot{x}^2 - \frac{1}{2}kx^2$$

Lagrangian mechanics	Newtonian mechanics
$\frac{\partial L}{\partial \dot{x}_i} = m\dot{x}, \frac{d}{dt}(m\dot{x}) = m\ddot{x}, \frac{\partial L}{\partial x} = -kx$ $F = m\ddot{x} + kx$	$\sum \bar{F} = m \cdot \bar{a}$ $F - kx = ma \rightarrow F = ma + kx$

The complexity of the terms increases as the number of degrees of freedom and variables.

Derive the equations of motion for the two-degree of freedom system.

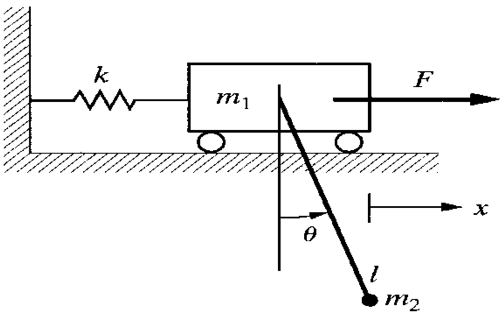


Fig. 3.13 Schematic of a cart-pendulum system.

In this system

- **It requires two coordinates, x and θ.**
- **It requires two equations of motion:**
  1. **The linear motion of the system.**
  2. **The rotation of the pendulum.**

$$\begin{bmatrix} F \\ T \end{bmatrix} = \begin{bmatrix} m_1 + m_2 & m_2 l \cos\theta \\ m_2 l \cos\theta & m_2 l^2 \end{bmatrix} \begin{bmatrix} \ddot{x} \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} 0 & m_2 l \sin\theta \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}^2 \\ \dot{\theta}^2 \end{bmatrix} + \begin{bmatrix} kx \\ m_2 g l \sin\theta \end{bmatrix}$$

Using the Lagrangian method, derive the equations of motion for the two-degree of freedom robot arm.

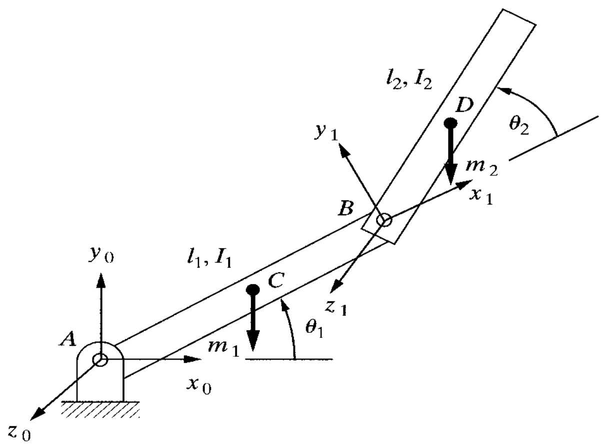


Fig. 3.14 A two-degree-of-freedom robot arm.

Follow the same steps as before

- Calculates the velocity of the center of mass of link 2 by differentiating its position:
- The kinetic energy of the total system is the sum of the kinetic energies of links 1 and 2.
- The potential energy of the system is the sum of the potential energies of the two links:

Thus, the same equations of motion have been obtained based on Lagrangian Formulation. Note that the Lagrangian Formulation is simpler and more systematic than the Newton-Euler Formulation. To formulate kinetic energy, velocities must be obtained, but accelerations are not needed. Remember that the acceleration computation was complex in the Newton-Euler Formulation, as discussed in the previous section. This acceleration computation is automatically dealt with in the computation of Lagrange's equations of motion. The difference between the two methods is more significant when the degrees of freedom increase, since many workless constraint forces and moments are present and the acceleration computation becomes more complex in Newton-Euler Formulation.

EFFECTIVE MOMENTS OF INERTIA

To simplify the equation of motion, Equations can be rewritten in symbolic form.

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \begin{bmatrix} D_{ii} & D_{ij} \\ D_{ji} & D_{jj} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_i \\ \ddot{\theta}_j \end{bmatrix} + \begin{bmatrix} D_{iii} & D_{ijj} \\ D_{jii} & D_{jjj} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1^2 \\ \dot{\theta}_2^2 \end{bmatrix} = \begin{bmatrix} D_{iii} & D_{ijj} \\ D_{jii} & D_{jjj} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \dot{\theta}_2 \\ \dot{\theta}_2 \dot{\theta}_1 \end{bmatrix} + \begin{bmatrix} D_i \\ D_j \end{bmatrix}$$

<u>DYNAMIC EQUATIONS FOR MULTIPLE-DEGREE-OF-FREEDOM ROBOTS</u>

Kinetic Energy Equations for a multiple-degree-of-freedom robot are very long and complicated, but can be found by calculating the kinetic and potential energies of the links and the joints, by defining the Lagrangian and by differentiating the Lagrangian equation with respect to the joint variables.

The kinetic energy of a rigid body with motion in three dimensions:

$$K = \frac{1}{2} m\overline{V}^2 + \frac{1}{2} \overline{\omega}\, \overline{h}_G$$

The kinetic energy of a rigid body in planar motion

$$K = \frac{1}{2} m\overline{V}^2 + \frac{1}{2} \overline{I}\omega^2$$

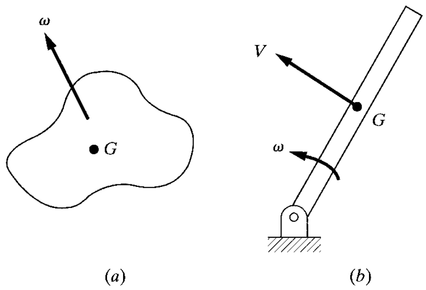


Fig. 3.15 A rigid body in three-dimensional motion and in plane motion.

<u>DYNAMIC EQUATIONS FOR MULTIPLE-DEGREE-OF-FREEDOM ROBOTS</u>

<u>Kinetic Energy</u>

The velocity of a point along a robot's link can be defined by differentiating the position equation of the point.

$$p_i = {}^{R}T_i r_i = {}^{0}T_i r_i$$

- The velocity of a point along a robot's link can be defined by differentiating the position equation of the point.

$$K_i = \frac{1}{2}\sum_{i=1}^{n}\sum_{p=1}^{i}\sum_{r=1}^{i} Trace\left(U_{ip}J_iU_{ir}^T\right)\dot{q}_p\dot{q}_r + \frac{1}{2}\sum_{i=1}^{n} I_{i(act)}\dot{q}_i^2$$

DYNAMIC EQUATIONS FOR MULTIPLE-DEGREE-OF-FREEDOM ROBOTS

Potential Energy

The potential energy of the system is the sum of the potential energies of each link.

$$P = \sum_{i=1}^{n} p_i = \sum_{i=1}^{n}[-m_i g^T \cdot ({}^0T_i\bar{r}_i)]$$

The potential energy must be a scalar quantity and the values in the gravity matrix are dependent on the orientation of the reference frame.

DYNAMIC EQUATIONS FOR MULTIPLE-DEGREE-OF-FREEDOM ROBOTS

Lagrangian Formulation of Robot Dynamics

Lagrangian Dynamics

In the Newton-Euler formulation, the equations of motion are derived from Newton's Second Law, which relates force and momentum, as well as torque and angular momentum. The resulting equations involve constraint forces, which must be eliminated in order to obtain closed-form dynamic equations. In the Newton-Euler formulation, the equations are not expressed in terms of independent variables, and do not include input joint torques explicitly. Arithmetic operations are needed to derive the closed-form dynamic equations. This represents a complex procedure that requires physical intuition, as discussed in the previous section.

An alternative to the Newton-Euler formulation of manipulator dynamics is the Lagrangian formulation, which describes the behavior of a dynamic system in terms of work and energy stored in the system rather than of forces and moments of the individual members involved. The constraint forces involved in the system are automatically eliminated in the formulation of Lagrangian dynamic equations. The closed-form dynamic equations can be derived systematically in any coordinate system.

$$L = K - P = \frac{1}{2}\sum_{i=1}^{n}\sum_{p=1}^{i}\sum_{r=1}^{i} Trace\left(U_{ip}J_iU_{ir}^T\right)\dot{q}_p\dot{q}_r + \frac{1}{2}\sum_{i=1}^{n} I_{i(act)}\dot{q}_i^2 - \sum_{i=1}^{n}[-m_i g^T \cdot ({}^0T_i\bar{r}_i)]$$

Inertia Matrix

In this section we will extend Lagrange's equations of motion obtained for the two degree of freedom. planar robot to the ones for a general *n* degree of freedom. robot. Central to

Lagrangian formulation is the derivation of the total kinetic energy stored in all of the rigid bodies involved in a robotic system. Examining kinetic energy will provide useful physical insights of robot dynamic. Such physical insights based on Lagrangian formulation will supplement the ones we have obtained based on Newton-Euler formulation.

DYNAMIC EQUATIONS FOR MULTIPLE-DEGREE-OF-FREEDOM ROBOTS

Robot's Equations of Motion

The Lagrangian is differentiated to form the dynamic equations of motion. The final equations of motion for a general multi-axis robot is below.

$$T_i = \sum_{j=1}^{n} D_{ij}\ddot{q}_j + I_{i(act)}\ddot{q}_i + \sum_{j=1}^{n}\sum_{k=1}^{n} D_{ijk}\dot{q}_j\dot{q}_k + D_i$$

where,

$$D_{ij} = \sum_{p=\max(i,j)}^{n} Trace(U_{pj}J_pU_{pi}^T)$$

$$D_{ijk} = \sum_{p=\max(i,j,k)}^{n} Trace(U_{pjk}J_pU_{pi}^T)$$

$$D_i = \sum_{p=i}^{n} -m_p g^T U_{pi}\bar{r}_p$$

Using the aforementioned equations, derive the equations of motion for the two-degree of freedom robot arm. The two links are assumed to be of equal length.

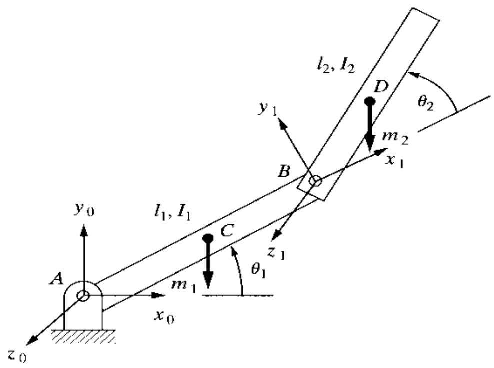


Fig: 3.16 The two-degree-of-freedom robot arm of Example

Follow the same steps as before

- Write the A matrices for the two links;
- Develop the hand for the robot.

The final equations of motion without the actuator inertia terms are the same as below.

$$T_1 = \left(\frac{1}{3}m_1l^2 + \frac{4}{3}m_2l^2 + m_2l^2C_2\right)\ddot{\theta}_1 + \left(\frac{1}{3}m_2l^2 + \frac{1}{2}m_2l^2C_2\right)\ddot{\theta}_2$$

$$+\left(\frac{1}{2}m_2l^2S_2\right)\dot{\theta}_2^2 + \left(m_2l^2S_2\right)\dot{\theta}_1\dot{\theta}_2 + \frac{1}{2}m_1glC_1 + \frac{1}{2}m_2glC_{12} + m_2glC_1 + I_{1(act)}\ddot{\theta}_1$$

$$T_2 = \left(\frac{1}{3}m_2l^2 + \frac{1}{2}m_2l^2C_2\right)\ddot{\theta}_1 + \left(\frac{1}{3}m_2l^2\right)\ddot{\theta}_2 + \left(\frac{1}{2}m_2l^2S_2\right) + \frac{1}{2}m_2glC_{12} + I_{2(act)}\ddot{\theta}_1$$

These centrifugal and Coriolis terms are present only when the multi-body inertia matrix is configuration dependent. In other words, the centrifugal and Coriolis torques are interpreted as nonlinear effects due to the configuration-dependent nature of the multi-body inertia matrix in Lagrangian formulation.

STATIC FORCE ANALYSIS OF ROBOTS

- Robot Control means Position Control and Force Control.
  - **Position Control**: The robot follows a prescribed path without any reactive force.
  - **Force Control** : The robot encounters with unknown surfaces and manages to handle the task by adjusting the uniform depth while getting the reactive force.
- Tapping a Hole - move the joints and rotate them at particular rates to create the desired forces and moments at the hand frame.
- Peg Insertion – avoid the jamming while guiding the peg into the hole and inserting it to the desired depth.

STATIC FORCE ANALYSIS OF ROBOTS

To relate the joint forces and torques to forces and moments generated at the hand frame of the robot.

$$\left[{}^{H}F\right] = \left[{}^{H}f_x \quad {}^{H}f_y \quad {}^{H}f_z \quad {}^{H}m_x \quad {}^{H}m_y \quad {}^{H}m_z\right]^T$$

- **f is the force and m is the moment along the axes of the hand frame.**

$$\delta W = \left[{}^{H}F\right]^T\left[{}^{H}D\right] = \left[T\right]^T\left[D_\theta\right]$$

- **The total virtual work at the joints must be the same as the total work at the hand frame.**

$$\delta W = \begin{bmatrix} f_x & f_y & f_z & m_x & m_y & m_z \end{bmatrix} \begin{bmatrix} dx \\ dy \\ dz \\ \partial x \\ \partial y \\ \partial z \end{bmatrix} = f_x dx + \cdots\cdots + m_z \delta z \qquad \left[T\right] = \left[{}^{H}J\right]^T\left[{}^{H}F\right]$$

TRANSFORMATION OF FORCES AND MOMENTS BETWEEN COORDINATE FRAMES

An equivalent force and moment with respect to the other coordinate frame by the principle of virtual work.

$$\begin{aligned} [F]^T &= [f_x \; f_y \; f_z \; m_x \; m_y \; m_z] \\ [D]^T &= [d_x \; d_y \; d_z \; \delta_x \; \delta_y \; \delta_z] \end{aligned} \quad \Rightarrow \quad \begin{aligned} [^{B}F]^T &= [^{B}f_x \; ^{B}f_y \; ^{B}f_z \; ^{B}m_x \; ^{B}m_y \; ^{B}m_z] \\ [^{B}D]^T &= [^{B}d_x \; ^{B}d_y \; ^{B}d_z \; ^{B}\delta_x \; ^{B}\delta_y \; ^{B}\delta_z] \end{aligned}$$

The total virtual work performed on the object in either frame must be the same.

$$\delta W = [F]^T [D] = [^{B}T]^T [^{B}D]$$

TRANSFORMATION OF FORCES AND MOMENTS BETWEEN COORDINATE FRAMES

Displacements relative to the two frames are related to each other by the following relationship.

$$[^{B}D] = [^{B}J][D]$$

The forces and moments with respect to frame B is can be calculated directly from the following equations:

$$\begin{aligned} ^{B}f_x &= \bar{n} \cdot \bar{f} & \qquad ^{B}m_x &= \bar{n} \cdot [(\bar{f} \times \bar{p}) + \bar{m}] \\ ^{B}f_y &= \bar{o} \cdot \bar{f} & \qquad ^{B}m_y &= \bar{o} \cdot [(\bar{f} \times \bar{p}) + \bar{m}] \\ ^{B}f_y &= \bar{o} \cdot \bar{f} & \qquad ^{B}m_z &= \bar{a} \cdot [(\bar{f} \times \bar{p}) + \bar{m}] \end{aligned}$$

Part A questions

1. Differentiate joint space and world space
2. Write the advantages of magnetic grippers.
3. What are the common types of motion that a manipulator can make?
4. What do you know about end effectors with unilateral and bilateral gripping action?
5. How are the robots classified on the basis of manipulator geometry?
6. Give two applications where vacuum grippers are widely used in robots.
7. What is inverse kinematics?
8. What are the types of actuators used for robot end effectors?

Part B questions

1. Compare joint space versus Cartesian space trajectory planning techniques also discuss briefly about the factors governing dynamic performance of a robot?
2. Explain (a) Manipulator path control
   (b) Manipulator dynamics
3. Discuss the different types of mechanisms with neat diagrams.
4. Describe the type of power sources used in the manipulation of grippers for robotics.
5. Derive the equation of force, F_x and F_y, in a static analysis of a two axis manipulator.
6. Discuss the various types of mechanical gripper mechanism with neat sketches.
7. Discuss suitable design of robot end effectors to grip objects like
   (a) Shafts
   (b) Rings
   (c) Flanges
   (d) Flat pieces