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# Locomotion study principles and applications

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# *Locomotion study principles and their applications*

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## Introduction:

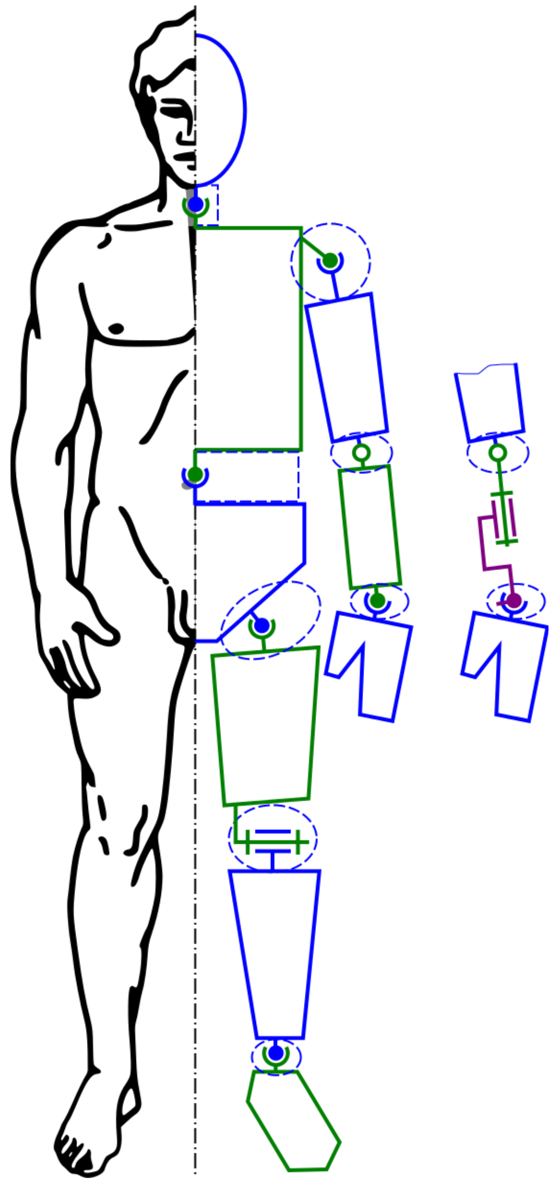
Isaac Asimov put four refined laws to protect the mankind from the intelligence generations of robots. We will need to apply those rules very soon to protect ourselves from any danger from robots.

- Law Zero: A robot may not injure humanity, or, through inaction, allow humanity to come to harm.
- Law One: A robot may not injure a human being, or, through inaction, allow a human being to come to harm, unless this would violate a higher order law.
- Law Two: A robot must obey orders given it by human beings, except where such orders would conflict with a higher order law.
- Law Three: A robot must protect its own existence as long as such protection does not conflict with a higher order law.

The term robotics refers to the study and use of robots. The term was first adopted by Asimov in 1941 through his short science fiction story, Runaround.

Based on the Robotics Institute of America (RIA) definition: "A robot is a reprogrammable multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks."

In this research I present the basic principles and key concepts of locomotion study with a small covering of the basics of robots and how they are categorized and dealt with according to specific characteristics in the robot. The aim is to give a glance about the simple principles of kinematics, dynamics and how to use them within controlling robots and present some visions and general suggestions to improve studying and controlling robots based on the principles taken from this research. In the second part, a general approach throw serial robots and their kinds in addition to some kinds of hybrid robots is given with a basic locomotion study of two famous models of robots. In the end, it is predicted to know the basic methods of modelling and applying those methods in robots.



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# Research:

## Locomotion study basics and principles:

For studying the robot in a mechanical way we have to know first the mechanical parts and components of the robot in addition to the features that describes the system. then, we can categorize the system and build a geometric model of the system. We can build the kinematic and dynamic modelling of the robot…

## The features of the system:

Those features describe the system workspace and we need to start by those descriptions which conclude the work envelope and the load capacity.

### *Robot Classification:*

The Japanese Industrial Robot Association divides robots in 6 different classes:

Class 1: Manual handling devices: A device with multi degrees of freedom that is actuated by an operator.

Class 2: Fixed sequence robot: A device that performs the successive stages of a task according to a predetermined and fixed program.

Class 3: Variable sequence robot: A device that performs the successive stages of a task according to a predetermined but programmable method.

Class 4: Playback robot: A human operator performs the task manually by leading the robot, which records the motions for later playback. The robot repeats the same motions according to the recorded information.

Class 5: Numerical control robot: The operator supplies the robot with a motion program rather than teaching it the task manually.

Class 6: Intelligent robot: A robot with the ability to understand its environment and the ability to successfully complete a task despite changes in the surrounding conditions under which it is to be performed.[1]

Although, there are many different classifications of robots based on other several types such as:" application- geometry- control…".

### *Work envelope:*

The work envelope includes every orientation and position the robot can achieve to accomplish a task in addition to the volume the robot occupies in space. As a conclusion, we can say that the work envelope of the robot is defined as the workspace plus the volume of the robot.

$$W_E = W_S + V_{Robot}$$

But, we can say that the work envelope is defined by the lengths of the links and the joints in addition to their limits of rotating and the valid angles they can move to preserve the ability to achieve the required task. We have to consider also the mechanical limits of the joints, links and rotating between axes.

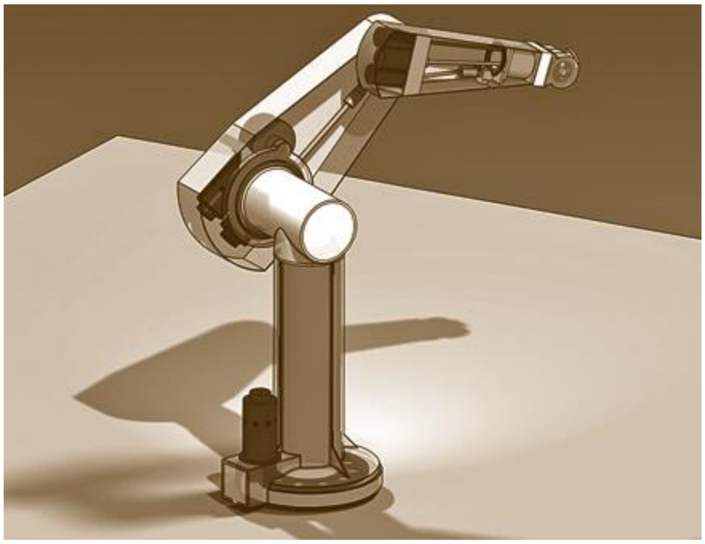

*Figure 1: the PUMA 560 robot arm*

[1] Jazar, R. N. 2010, Theory of applied robotics: kinematics, dynamics, and control (Springer Science & Business Media.

Most of the open-loop chain manipulators are designed with a wrist subassembly attached to the main three links assembly. Therefore, the first three links are long and are utilized for positioning while the wrist is utilized for control and orientation of the end-effector. This is why the subassembly made by the first three links is called the arm, and the subassembly made by the other links is called the wrist.[2]

## *Load capacity:*

This specification varies widely between different kinds of robots and their structures, it is simply the load that the robot can take during its work period, and this depends on the robot's topology and general kind like the serial or open loop robots and closed loop robots and it is always accompanied by the study of the mechanical limits and bad situations (those situations include every situation that might occur with the actuators).

## *Kinematic skeleton:*

The kinematic skeleton depends on many factors such as the required shape and features of the actuators which depends on the task and its required abilities such as (precision, torque, load limit, speed, acceleration….). it is necessary to understand the kinematic skeleton of the robot so we can control it properly and upgrade its functions to the maximum limits.

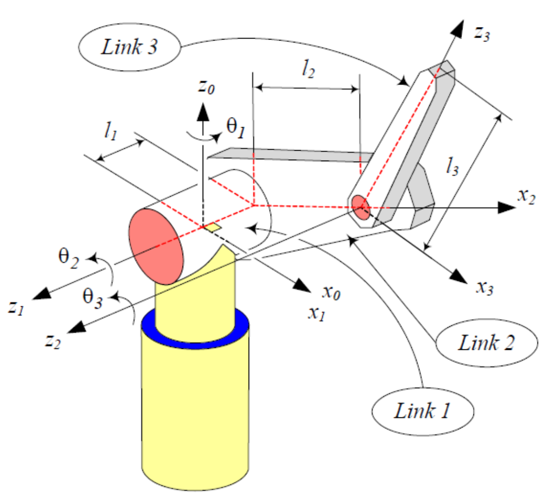


*Figure 2: the kinematic skeleton of the puma 560 arm represented in Figure(1)*

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[2] Jazar, R. N. 2010, Theory of applied robotics: kinematics, dynamics, and control (Springer Science & Business Media.

Six degrees of freedom (DOFs) are the minimum required to place the end-effector or tool of a robotic manipulator at any arbitrary location (position and orientation) within its accessible workspace.

## Mechanical components of the robot:

The robotic manipulators are composed of many links and joints to connect between them to form a kinematic chain or skeleton. But, the robot as a system is manipulator or rover, a wrist, an end-effector, actuators, sensors, controllers, processors, and software.[3]

### *Links:*

According to [4] the individual rigid bodies that make up a robot are called links. In robotics we sometimes use the definition arm instead. A robot arm or a robot link is a rigid member that may have relative motion with respect to all other links. From the kinematic point of view, two or more members connected together such that no relative motion can occur among them are considered a single link.[4]

### *Joints:*

Joints connect the parts and links of the robot; it allows either rotary or linear movements with prismatic or revolute joints. In addition to spherical joints, ball-in-socket joints plus the hook-type universal joint.

Integration of the mechanical structure of the robot with its joint mechanism, which includes the actuator and joint motion sensor, is a source of structural flexibility. Deformation in the joint at the bearing housings can reduce shaft and gear preloads, allowing backlash or free play, which reduces precision. Structural flexibility can also

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[3] Siciliano, B. & O. Khatib 2008, Springer handbook of robotics (Springer Science & Business Media.

[4] Jazar, R. N. 2010, Theory of applied robotics: kinematics, dynamics, and control (Springer Science & Business Media.

introduce changes in gear center spacing, introducing forces and torques and associated deflection, binding, jamming, and wear.[5]

## Other components of the robot:

### *Manipulators:*

Manipulators which are consisted of links, joints plus any structural materials. A manipulator makes the main body of the robot. Sometimes manipulators and robots are used as the same meaning but, as a scientific definition a manipulator becomes a robot when we add a wrist or a joint or any kind of actuators.

### *End-effector:*

The end-effector is usually the last part in the kinematic sequence. It is the part which is mounted to the last link which varies according to the robot's job or mission. The simplest end-effector is a gripper, which is usually capable of only two actions: opening and closing. The arm and wrist assemblies of a robot are used primarily for positioning the end-effector and any tool it may carry.[6]

There is also extensive research on the development of anthropomorphic hands. Such hands have been developed for prosthetic use in manufacturing. Hence, a robot is composed of a manipulator or mainframe and a wrist plus a tool. The wrist and end-effector assembly is also called a hand.

[5] Siciliano, B. & O. Khatib 2008, Springer handbook of robotics (Springer Science & Business Media.

[6] Jazar, R. N. 2010, Theory of applied robotics: kinematics, dynamics, and control (Springer Science & Business Media.

## Kinematics:

Spatial, rigid-body kinematics can be viewed as a comparative study of different ways of representing the pose of a body. Translations and rotations, referred to in combination as rigid-body displacements, are also expressed with these representations. No one approach is optimal for all purposes, but the advantages of each can be leveraged appropriately to facilitate the solution of different problems.[7]

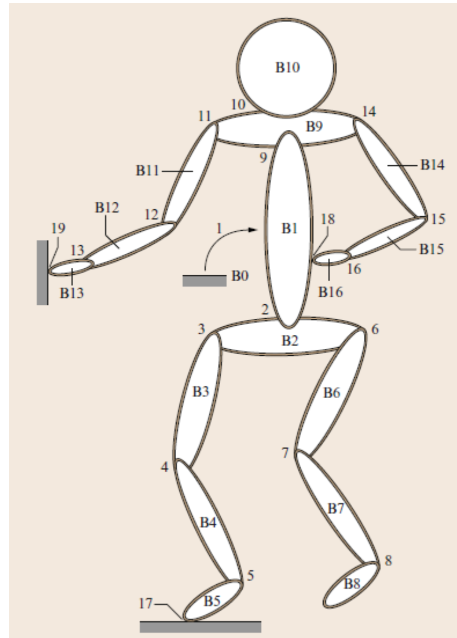

*Figure 3: Humanoid robot example. Note: to distinguish between*

Since Links and joints are considered a rigid body parts in robotics, rigid-body displacement took a central space in Robotics. Vectors and Algebra matrices are used to describe the general rotation and orientation of different coordinate references and axis according with respect to each other and to a fixed general frame.

Since the arms of a robot may rotate or translate with respect to each other, body-attached coordinate frames A, B, C, · · · or B1, B2, B3, · · · will be established along with the joint axis for each link to find their relative configurations, and within the reference frame G.

The position of one link B relative to another link A is defined kinematically by a coordinate transformation ATB between reference frames attached to the link.[8]

Basically, the analytical form of the kinematic movements is composed out of two ways of movement: translation of different points in a designated path and the rotation kinematics

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[7] Siciliano, B. & O. Khatib 2008, Springer handbook of robotics (Springer Science & Business Media.

[8] Jazar, R. N. 2010, Theory of applied robotics: kinematics, dynamics, and control (Springer Science & Business Media.

which is the rotating of the body or the links around specific points which are usually the same points of the translation movements.

Consider a rigid body with a fixed point. Rotation about the fixed point is the only possible motion of the body. We represent the rigid body by a body coordinate frame B, that rotates in another coordinate frame G, as is shown in Figure 2.1. We develop a rotation calculus based on transformation matrices to determine the orientation of B in G, and relate the coordinates of a body point P in both frames.

## Rotation Matrices:

The orientation of coordinate frame $i$ relative to coordinate frame $j$ can be denoted by expressing the basis vectors $(\hat{x}_i \hat{y}_i \hat{z}_i)$ in terms of the basis vectors $(\hat{x}_j \hat{y}_j \hat{z}_j)$. This yields $({}^j\hat{x}_i \, {}^j\hat{y}_i \, {}^j\hat{z}_i)$, which when written together as a 3×3 matrix is known as the rotation matrix. The components of ${}^jR_i$ are the dot products of basis vectors of the two coordinate frames.

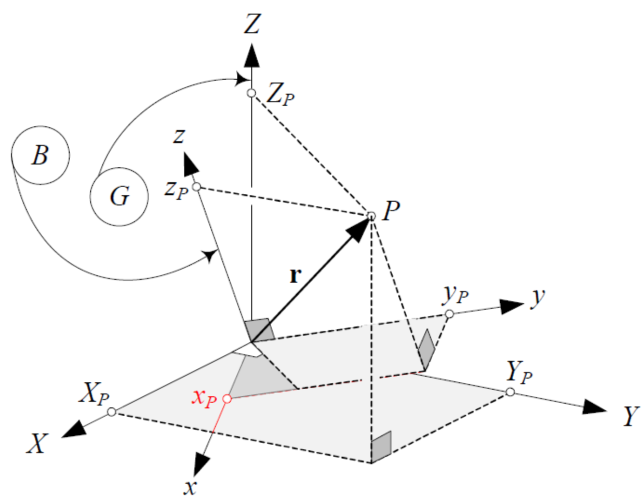


*Figure 4: a representation of the relation between rotation matrices geometrically*

$$
{}^jR_i = \begin{pmatrix} \vec{x}_i . \vec{x}_j & \vec{y}_i . \vec{x}_j & \vec{z}_i . \vec{x}_j \\ \vec{x}_i . \vec{y}_j & \vec{y}_i . \vec{y}_j & \vec{z}_i . \vec{y}_j \\ \vec{x}_i . \vec{z}_j & \vec{y}_i . \vec{z}_j & \vec{z}_i . \vec{z}_j \end{pmatrix}
$$

Because the basis vectors are unit vectors and the dot product of any two unit vectors is the cosine of the angle between them, the components are commonly referred to as direction cosines.[9]

$$R_z(\theta) = \begin{pmatrix} Cos(\theta) & -Sin(\theta) & 0 \\ Sin(\theta) & Cos(\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$R_Y(\theta) = \begin{pmatrix} Cos(\theta) & 0 & Sin(\theta) \\ 0 & 1 & 0 \\ -Sin(\theta) & 0 & Cos(\theta) \end{pmatrix}$$

$$R_X(\theta) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & Cos(\theta) & -Sin(\theta) \\ 0 & Sin(\theta) & Cos(\theta) \end{pmatrix}$$

According to the last matrices, we can see for sure that every rotation matrix contains nine elements, although only three elements or coordinates are required to define a point in space, but we defined extra six elements which represent relationships between coordinates in the space.

And there are many theories concerning modelling and how to express the status and the values of the kinematic chain. In the next figures we can observe many rotation matrices with different sensations of orientation.

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[9] Siciliano, B. & O. Khatib 2008, Springer handbook of robotics (Springer Science & Business Media.

$$ {}^{j}R_i = \begin{pmatrix} C_\alpha C_\beta & C_\alpha S_\gamma S_\beta - C_\gamma S_\alpha & C_\gamma C_\alpha S_\beta + S_\alpha S_\gamma \\ S_\alpha C_\beta & S_\gamma S_\beta S_\alpha + C_\gamma C_\alpha & S_\beta S_\alpha C_\gamma - S_\gamma C_\alpha \\ -S_\beta & C_\beta S_\gamma & C_\beta C_\gamma \end{pmatrix} $$

$$ {}^{j}R_i = \begin{pmatrix} C_\phi C_\theta & C_\phi S_\psi S_\theta - C_\psi S_\phi & C_\psi C_\phi S_\beta + S_\phi S_\psi \\ S_\phi C_\theta & S_\psi S_\theta S_\phi + C_\psi C_\phi & S_\theta S_\phi C_\psi - S_\psi C_\phi \\ -S_\theta & C_\theta S_\psi & C_\theta C_\psi \end{pmatrix} $$

According to the thesis and principles approved in [4], for a minimal representation, the orientation of coordinate frame $i$ relative to coordinate frame $j$ can be denoted as a vector of three angles $(\alpha, \beta, \gamma)$. These angles are known as Euler angles when each represents a rotation about an axis of a moving coordinate frame.

And we can apply the earlier rotation matrices in different representations of frames according to each other which are presented as solutions of $(\alpha, \beta, \gamma)$.

| |
|---|
| ${}^{j}R_i = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix}$ |
| $\beta = A\tan 2(-r_{31}, \sqrt{r_{11}^2 + r_{21}^2})$ |
| $\alpha = A\tan 2(\frac{r_{21}}{Cos(\beta)}, \frac{r_{11}}{Cos(\beta)})$ |
| $\gamma = A\tan 2(\frac{r_{32}}{Cos(\beta)}, \frac{r_{33}}{Cos(\beta)})$ |

## Euler Angles:

For a minimal representation, the orientation of coordinate frame *i* relative to coordinate frame *j* can be denoted as a vector of three angles $(\alpha, \beta, \gamma)$. These angles are known as Euler angles when each represents a rotation about an axis of a moving coordinate frame. In this way, the location of the axis of each successive rotation depends upon the preceding rotation(s), so the order of the rotations must accompany the three angles to define the orientation. For example, the symbols $(\alpha, \beta, \gamma)$ are used throughout this handbook to indicate $Z$–$Y$–$X$ Euler angles. Taking the moving frame *i* and the fixed frame *j* to be initially coincident, $\alpha$ is the rotation about the $\hat{z}$ axis of frame *i*, $\beta$ is the rotation about the rotated $\hat{y}$ axis of frame *i*, and finally, $\gamma$ is the rotation about the twice rotated $\hat{x}$ axis of frame *i*.

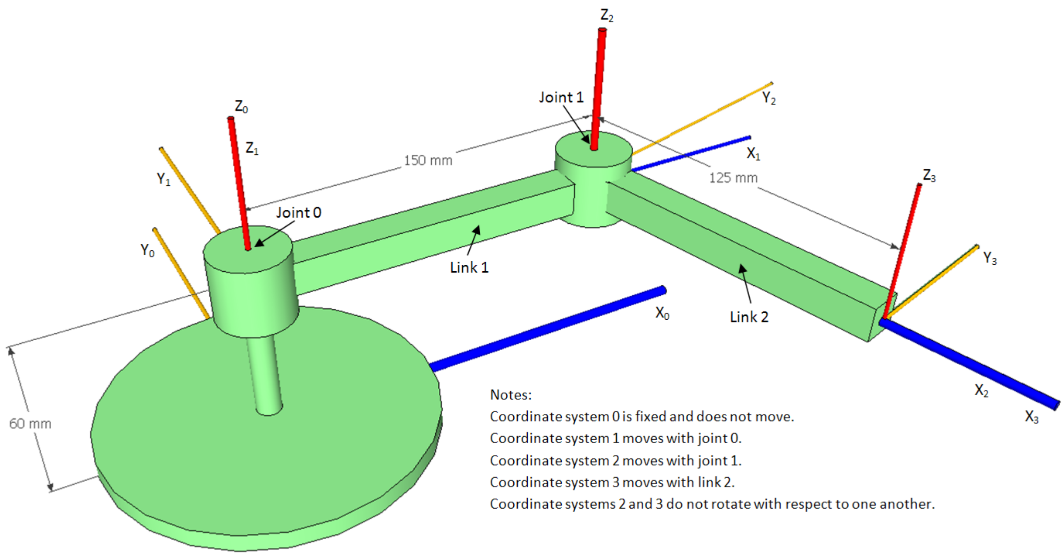



*Figure 5: representation of the geometrical study of 2d workspace arm or we can call it (SCARA)*

## Homogeneous Transformations:

The kinematic study of any robot or machine basically consists of kinematic rotation and translation matrices, but we can develop many solutions and more effective ways of representations and that is where the homogeneous transformations comes in.

The homogeneous transformations represent the rotation values around every axis in space in addition to the translation of the designated point on X-Y-Z.

The preceding sections have addressed representations of position and orientation separately. With homogeneous transformations, position vectors and rotation matrices are combined together in a compact notation. Any vector $i_r$ expressed relative to the $i$ coordinate frame can be expressed relative to the $j$ coordinate frame if the position and orientation of the $i$ frame are known relative to the $j$ frame. The position of the origin of coordinate frame $i$ relative to coordinate frame $j$ can be denoted by the vector

${}^{j}p_i = ({}^{j}p_i^{x} \; {}^{j}p_i^{y} \; {}^{j}p_i^{z})^T$ .

The orientation of the frame i according to frame j is donated by the rotation matrices ${}^{j}R_i$ as follows: ${}^{j}r = {}^{j}R_i^{i} + {}^{j}p_i$ and we can write the previous equation as follows

$$\begin{pmatrix} {}^{j}r \\ 1 \end{pmatrix} = \begin{pmatrix} {}^{j}R_i & {}^{j}p_i \\ 0^T & 1 \end{pmatrix} \begin{pmatrix} {}^{i}r \\ 1 \end{pmatrix}$$

Where:

$${}^{j}T_i = \begin{pmatrix} {}^{j}R_i & {}^{j}p_i \\ 0^T & 1 \end{pmatrix}$$ [10]

## Joint kinematics:

A joint is a connection point between two rigid links in the kinematic chain of the robot and we can represent it as a matrix which donate the coordinates in space of one link with respect to the source link.

[10] Siciliano, B. & O. Khatib 2008, Springer handbook of robotics (Springer Science & Business Media

A joint model describes the motion of a frame fixed in one body of a joint relative to a frame fixed in the other body. The motion is expressed as a function of the joint's motion variables, and other elements of a joint model include the rotation matrix, position vector, free modes, and constrained modes.[11]

There are many kinds of joints according to the degree of freedom and the architecture of the joint with respect to the degrees between the rotation axes they can be categorized to lower pair joints with high degree of freedom and low degree of freedom and higher pair joints:

| LOWER PAIR JOINTS | HIGHER PAIR JOINTS |
|---|---|
| HELICAL | ROLLING CONTACT |
| REVOLUTE | |
| PRISMATIC | |
| SPHERICAL | |
| CYLINDRICAL | |
| PLANAR | |

## Kinematic Models:

In any representation of the rotation or translation between frames we can form many equations between rotation values of the joints and coordinates of the end effectors of the robot and these equations and relations we call models. Models give us an effective and direct way to find ultimate solutions of the kinematic chain or model. There are two basic models of kinematics: "Forward and Inverse" and they will be represented as follows:

[11] Jazar, R. N. 2010, Theory of applied robotics: kinematics, dynamics, and control (Springer Science & Business Media.

### 1- *Direct Kinematic Model (DKM):*

The direct kinematic model denote the solutions of the X-Y-Z coordinates based on the input of the $\theta n$ rotation value around the axes of the kinematic chain.

$$\{\theta_1, \theta_2, \theta_3, \theta_4, \ldots \theta_n\} \longrightarrow (X, Y, Z)$$

The forward kinematics problem for a serial-chain manipulator is to find the position and orientation of the end-effector relative to the base given the positions of all of the joints and the values of all of the geometric link parameters. Often, a frame fixed in the end-effector is referred to as the *tool frame*, and while fixed in the final link *N*, it in general has a constant offset in both position and orientation from frame *N*. Likewise, a *station frame* is often located in the base to establish the location of the task to be performed. This frame generally has a constant offset in its pose relative to frame 0, which is also fixed in the base.[12]

We can find the solutions of the DKM by performing equations to relate between the rotation of the axes and the tool frame. As represented previously we represent every joint as a matrix with the rotation values and translation values and it can be represented as homogeneous matrices of the joints, we can connect between the joints as follows:

$$^{0}T_6 = {}^{0}T_1 . {}^{1}T_2 . {}^{2}T_3 . {}^{3}T_4 . {}^{4}T_5 . {}^{5}T_6$$

$$^{0}T_6 = \begin{pmatrix} r_{11} & r_{12} & r_{13} & {}^{0}p_6^x \\ r_{21} & r_{22} & r_{23} & {}^{0}p_6^y \\ r_{31} & r_{32} & r_{33} & {}^{0}p_6^z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

[12] Siciliano, B. & O. Khatib 2008, Springer handbook of robotics (Springer Science & Business Media

## 2- *Inverse Kinematic Model(IKM):*

The IKM is most used with control techniques of robots and machines, it represents the relation between the joint rotation values and the coordinates of the tool frame in space.

$$(X,Y,Z)\longrightarrow\{\theta_1,\theta_2,\theta_3,\theta_4,\ldots\theta_n\}*n$$

What are the joint variables for a given configuration of a robot? This is the inverse kinematic problem. The determination of the joint variables reduces to solving a set of nonlinear coupled algebraic equations. Although there is no standard and

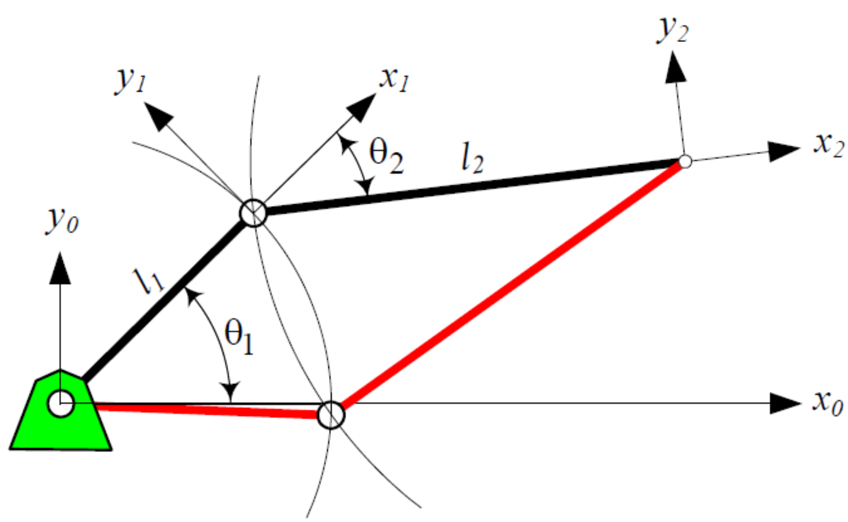



*Figure 6: a Scara arm geometrical representation*

generally applicable method to solve the inverse kinematic problem, there are a few analytic and numerical methods to solve the problem. The main difficulty of inverse kinematic is the multiple solutions.[13]

Where n is the number of groups of solutions. It can be seen that the IKM gives us the ultimate solution of the tool frame we want; it is simply the solutions of the

[13] Jazar, R. N. 2010, Theory of applied robotics: kinematics, dynamics, and control (Springer Science & Business Media

rotation and translation values of joints and links of the robot which are usually represented by actuators according to the desired X-Y-Z coordinates in space.

## Control principles and applications:

The advanced control principles revolutionized the entire robotics world and especially during the last decade. Most of the control theories are inspired by the construction and behavior of the human body or any constructions of other creatures.

The most important factor for the robot to preserve the ability of performing different tasks. There are two kinds of stability which conclude: "static - walking". And we define and apply different movement gaits that achieve the desired stability and performance. A gait is defined as a sequence of leg motions coordinate with a sequence of body motions for moving the overall body of the robot in the desired direction and orientation from one place to another. Some examples found in the literature are for instance the periodic gaits, free gaits or a combination of both approaches. A gait is called periodic when similar states of the same leg during successive strokes occur at the same interval for all legs. The free gait or also called non-periodic gait is when each leg can move on a free chosen interval and own stroke algorithm. [14]

Periodic gaits are suitable for smooth terrain. But, the free gaits are much more effective on rough terrain with obstacles. A lot of research is done on free gaits to find graphical and analytical methods. The difficulty with these methods is the complexity and interactions. Therefor genetic algorithms (GAs) are mostly used for free gait implementation. GA are population-based search and optimization techniques which work on Darwin's principle of natural selection. GA has shown to be a powerful tool for global optimization and has been

[14] Woering, R. 2011, University of Technology Eindhoven

used as a key element in many learning techniques. Another way then using GA is a fuzzy logic controller (FLC), a potential tool for handing imprecision and uncertainty. Off course, in controlling robots, what is most important is maintaining the stability of the system which guarantee the ability to perform tasks with a much better quality.

Stability is in short words the balancing of the robot. There are 2 types if stability: static and dynamic. Static stability applies when there are no extra movements or forces needed to prevent the robot from falling over. The Center of Mass (CoM) of the robots is at all-time within the support pattern of the legs which have ground contact such as figure (8).

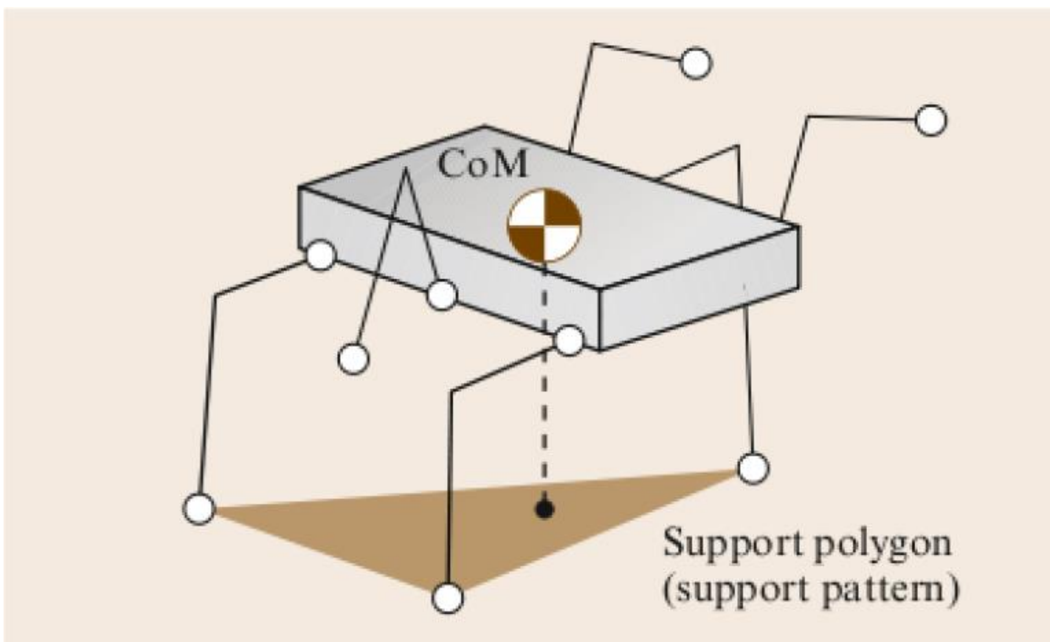



*Figure 7: Support polygon (support pattern) of a multi legged robot with the CoM (Center of Mass).*

Dynamic stability is needed when the CoM is outside or on the border of the support pattern. When the CoM is outside the support pattern the robot will fall over when no additional forces and movement are made with the legs (balancing).[15]

[15] Woering, R. 2011, University of Technology Eindhoven.

## PID Control:

Most often dynamical systems are controlled by control laws designed according to the methods of classical and modern control. These methods are applicable if a relative precise model of the dynamic system being controlled is available. Planned jointed trajectories constitute the reference for the robot control system. Therefor an inverse dynamic model can be formulated. The general control architecture of multi legged robots for an example locomotion system is shown in the next figure. The trajectory is planning is held in the Cartesian space, but the control is performed in the joint space, which requires the integration of the inverse kinematic model in the forward path. The control algorithm considers an external postilion and velocity feedback and an internal feedback loop with information of the foot ground interaction force.

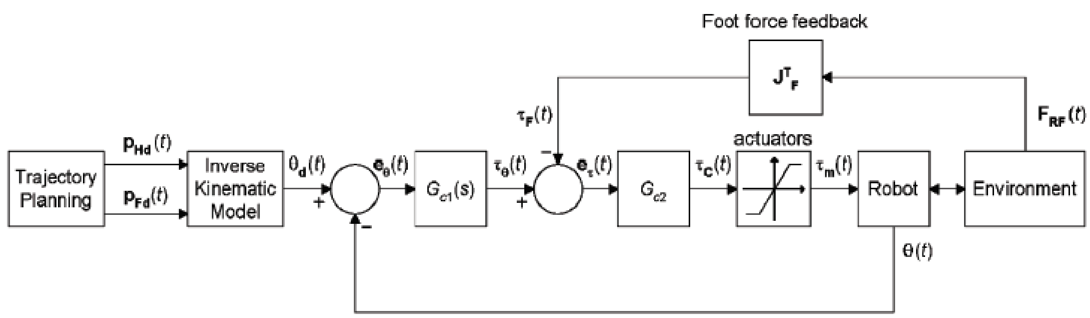
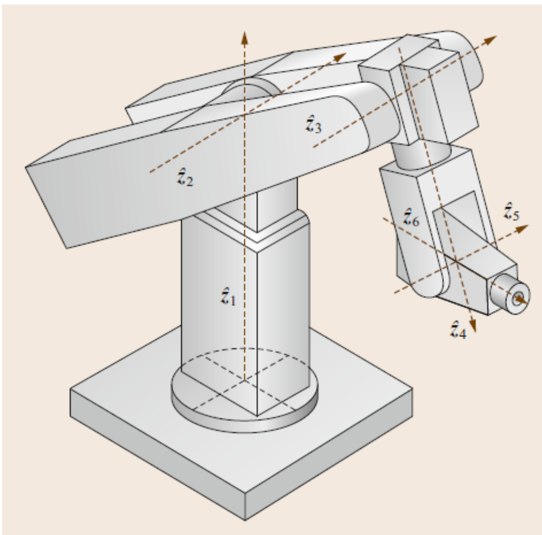
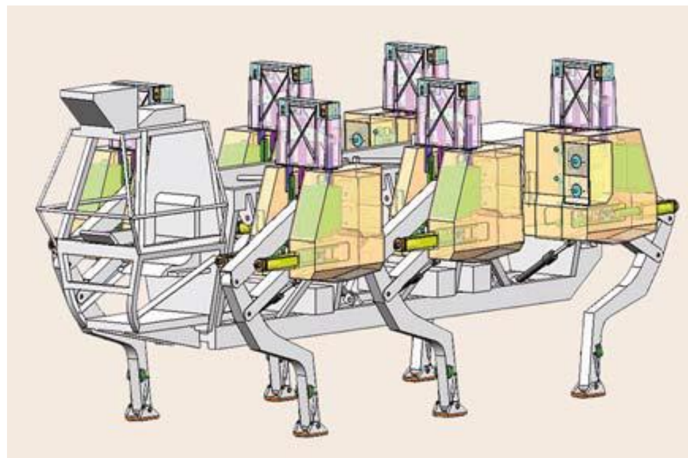


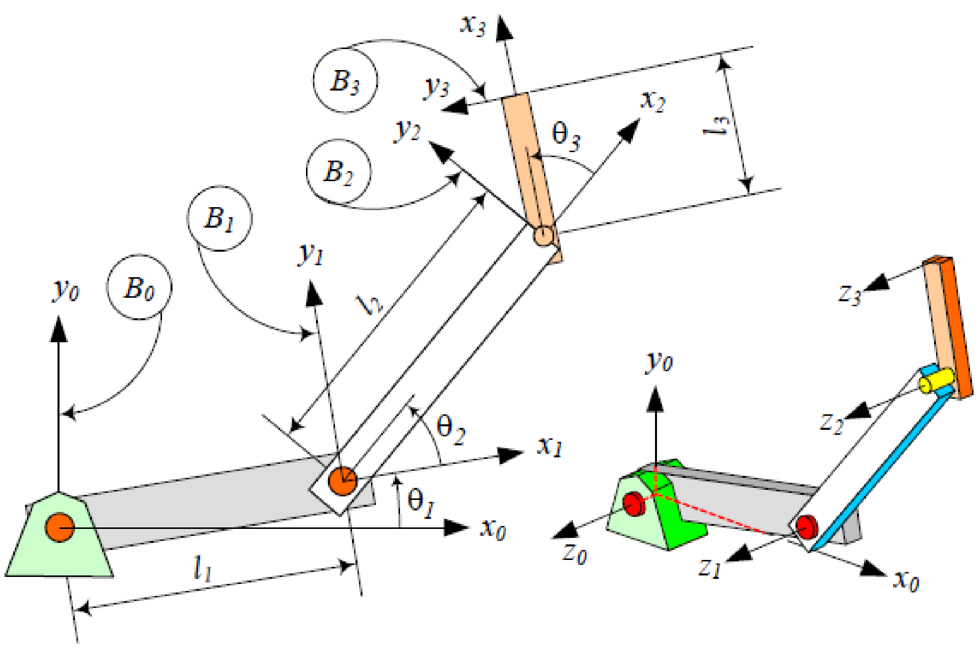

*Figure 8: the general skeleton of the control system work progress using the kinematic models*

We can develop the control of the robot and exceed the expected expectations by using the Genetic Algorithms in mastering the general behavior of the robot. A genetic algorithm (GA) is a search technique for finding optimal solutions for analytical problems. The term genetic algorithm is based on is evolutionary approach of reaching the solution. The algorithm will "punish" wrong trials and reward attempts which come closer to the desired result. Genetic algorithms are a particular class of evolutionary algorithms (EA) that use techniques inspired by evolutionary biology such as inheritance, mutation, selection, and crossover. Cyclic Genetic Algorithms are designed for the cyclic decision problems like the adaptive gait development for hexapod robots. The approach is to develop a model capable of representing all states of the robot and use a cyclic genetic algorithm to train the model to walk forward, backward or in any desired orientation.

*     *     *     *     *





## Resources:


1- Woering, R. 2011, University of Technology Eindhoven.

2- Jazar, R. N. 2010, Theory of applied robotics: kinematics, dynamics, and control (Springer Science & Business Media.

3- Tedeschi, F. & G. Carbone 2014, Robotics, 3, 181.

4- Siciliano, B. & O. Khatib 2008, Springer handbook of robotics (Springer Science & Business Media.


## Table of figures:

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In this research we present the locomotion study principles with its applications to robotics world. The concepts represented in this research are essential for building the model of any robot and the applications reaches the simulation of any system and its control methods.

As a development of this research the dynamic locomotion systems can be studied and I strongly advice with constructing the dynamic models and dividing the locomotion system gaits into passive and active for exceeding a better quality of performance.