A short treatise on robots' geometry, kinematics, and dynamics.

Author: Lekan Molu

Dissemination: Microsoft Research RL Group,

New York City, NY 10012

May 30, 2022

Table of Contents

Table of Contents

Table of Contents

Standard Texts – Modeling and Control

Robot Modeling and Control

Spong, Mark W., Seth Hutchinson, and Mathukumalli Vidyasagar. Robot modeling and control. Vol. 3. New York: Wiley, 2006.

Mathematical Modeling of Robots

Murray, R. M., Li, Z., & Sastry, S. S. (1994). A Mathematical Introduction to Robotic Manipulation. In Book (Vol. 29). https://doi.org/10.1.1.169.3957

Texts – Modeling, Control, and Mechanisms

Robot Modeling and Control

Lynch, K. M., & Park, F. C. (2017). Modern Robotics Mechanics, Planning, and Control.

Mechanisms' Kinematic Geometry

Hunt, Kenneth H., and Kenneth Henderson Hunt. Kinematic geometry of mechanisms. Vol. 7. Oxford University Press, USA, 1978.

Texts – Screws and Kinematics

Screw Theory

Ball, Robert Stawell. A Treatise on the Theory of Screws. Cambridge university press, 1998.

Mechanisms' Kinematic Geometry

Hunt, K. H. (2019). Structural Kinematics of In-Parallel-Actuated Robot-Arms. 105(December 1983), 705–712.

Outline

Mechanism Components

Freedoms, Constraints, and Mobility.

Kinematic Geometry: Pairs, linkages, and mechanisms.

Motion of linkages: Screws, and spatial motions.

Freedom and Mobility: Freedoms, unfreedoms, connectivity, mobility;

Grübler-Kutzbach's mobility criterion and examples.

Definition of a Mechanism

Definition (Author's Definition)

A connection of mechanical, magnetic, electrical, hydraulic, or pneumatic components forming an assemblage, meant for moving rigid, semi-rigid or non-rigid bodies via a controlled generation of (sometimes) motion.

Kenneth Hunt (1978)

A means of *transmitting*, *controlling*, or *constraining* the relative movement.

Mechanisms

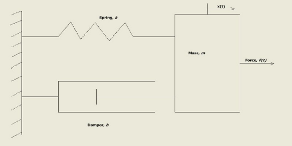
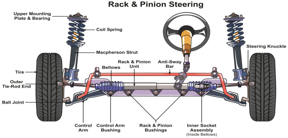
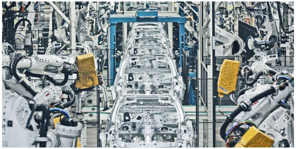
Joints and links

Joints are a result of the connecting points between rigid links. Links may be rigid mechanical parts, elastic, (vulcanized) rubber components, diaphragms, conveyor belts, spring-damper systems e.t.c.

Rigid Mechanism

Our chief focus will be rigid links, pairs, components and mechanisms in general.

Mechanisms Examples

Spring-Mass-Damper System	Excavator
	
Car suspension	**Daimler Plant**
	

Open Kinematic Chains

Chains

Open kinematic chains are based off the anthropomorphic construction of the human hand with cantilevered beam structures.

Chain Mechanisms and Error Amplification

Amplifies errors from waist (or base frame) all the way to the tool frame. Control difficult.

Control

Feedforward control: High power and precision hydraulic actuators for servo motors.
Sensory feedback control: Force sensing (Ernst, 1962).

Chains
Open kinematic chains are based off the anthropomorphic construction of the human hand with cantilevered beam structures.

Chain Mechanisms and Error Amplification
Amplifies errors from waist (or base frame) all the way to the tool frame. Control difficult.

Control
Feedforward control: High power and precision hydraulic actuators for servo motors.
Sensory feedback control: Force sensing (Ernst, 1962).

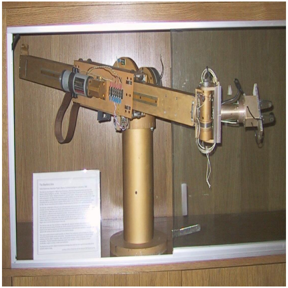
The PUMA arm is the world's first serial kinematic chain. Developer: Victor Scheinman, Stanford student in the '50's. Made several iterations. Patent Rights: Joe Engelberger, (Danbury Unimation, 1961). Joe – father of robotics – created world's first robotics company in '61.

Open Kinematic Robot Mechanisms

Definition (Ken Salisbury Jr., 1982)

"*[Robots are] our fascination with constructing mechanical analogues of ourselves... [this fascination] has led us to place all sorts of hopes and expectations in robot capabilities.*"

The Stäubli PUMA Robot (1956).



The Stanford Arm (Infolab 1969).

Open Kinematic Chains

Open kinematic chains provide unstructured environmental interaction.

Project MAC, MIT.

Tomovic and Boni's pressure sensed grasp.

Binary robot vision system (McCarthy et al, 1963).

Open Kinematic Chains

Stanford Manipulator.

Boston arm.

The AMF (American Machines and Foundry) arm.

General electric's walking robot (1969).

Long Walk Towards Direct Drive Robot Arms

The 50's, 60's nd 70's witnessed use of hydraulics for (feedforward) position control.

For feedback control, force sensors and pressure sensors were used in closed-loop scenarios.

Electrical actuation meant that robots had to be operated at high speeds. Needs for gear reduction for safe operations at low speeds.

With gear reduction came backlash, friction, and associated expenses.

The 50's, 60's nd 70's witnessed use of hydraulics for (feedforward) position control.

For feedback control, force sensors and pressure sensors were used in closed-loop scenarios.

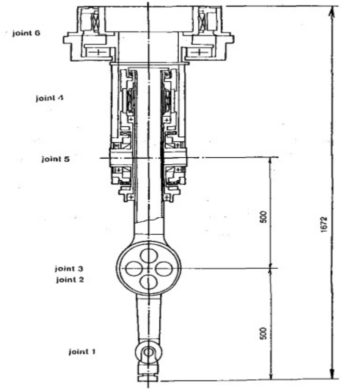
Electrical actuation meant that robots had to be operated at high speeds. Needs for gear reduction for safe operations at low speeds.

With gear reduction came backlash, friction, and associated expenses.

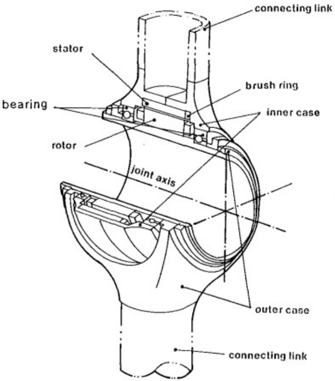
CMU DD I/II Arms: Workspace is donut shaped. OD: 90cm; ID: 21.7cm; $1.8m^2$ workspace area. Built by Harry Asada. Structural design similar to aircraft gimbal arm; Uses Samarium Cobalt rare earth magnet brushless DC motors on first 3 joints, and AlNiCo magnets on tip joints. No belts, transmissions making for faster transmitting of motions, less friction, low energy, low compliance. Each joint has complex AL housing which enables: (i) Control of geometrical relationships of bearing assembly; (ii) Control of servo components to bearing assembly; (iii) Controls of rotational axes to consecutive joints.

Direct Drive Robot Mechanism: CMU DD I Arm

Along came Harry Asada.

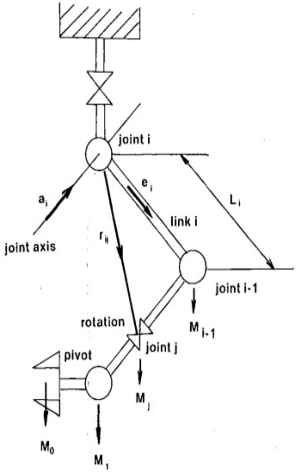


Arm Schematics Transmission

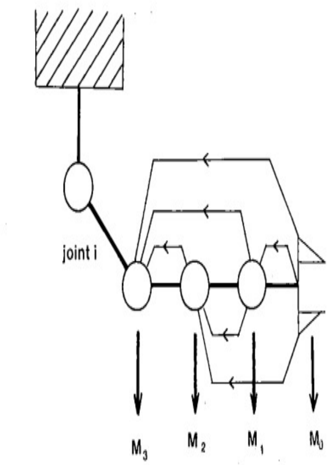


Joint schematic

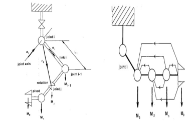
Direct Drive Robot Mechanism: CMU DD I Arm



Kinematic model



Errors Transmission

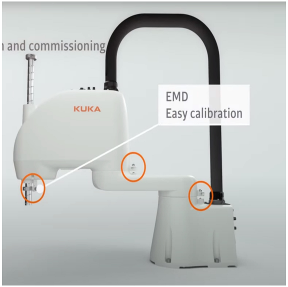


Kinematic model   Errors Transmission

First direct-drive robot without a gearbox. Selective compliance in X-Y directions given its articulated jointed arms. One-freedom motion along Z direction given its constrained arm New generations such as Cobra i600/i800 include power amplifiers, system and servo controls etc embedded in the robot's base. Kuka Scara arm: Lightweight, fast, powerful, low maintenance, energy consumption, investment costs etc.

SCARA Robot Mechanisms

The Adept One SCARA robot (Debuted 1984).



Kuka's SCARA arm, 2022. ©Kuka Robotics

Serial mechanisms research in the 80's

Mechanisms in the 80's

With the 80's came the arrival of PCs. Lots of research went into computational algorithms for the kinematics and kinetics of (mostly) anthropomorphic robot arms.

Active control schemes

Efficient recursive Lagrangian and computational methods for the gravitational and Coriolis forces in Newton-Euler equations.

Feedback Linearization

Dynamics feedback linearization for precise bounds on manipulator performance.

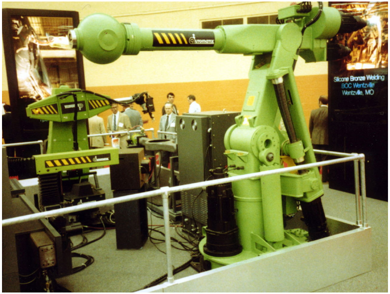
Serial mechanisms research in the 90's

Automatix

Reconfigurable robots for various assembly ops.

Robotworld

First industrial-scale reconfigurable robot and with machine vision components. RAIL scripting OS originally based on Motorola 68000, later on replaced by Apple Macintosh II.



©Wikipedia

Outline

Mechanism Components

Kinematic geometry. Rigid bodies. Joints.

Joints: Curve and straight line contacts; joint closure;

Pairs; couplings.

Lower pairs and linkages, Higher and lower pairs.

Motions: Planar and spherical motions.

Synthesis: Type-, number-, and size-syntheses.

Preamble – Mechanics Overview.

Mechanics.

Mechanics takes an indirect approach to the study of nature –via bodies – essentially mathematical abstractions of common natural things; the mass is an allocation in *place* to each body; geometry, deals with the theory of places; geometry is the bedrock of robotics, control theory, and many fields of modern engineering and the physical sciences.

Preamble – Mechanics Overview.

Definition (Motion.)

When a place undergoes body transformation in the course of time, we shall have motion.

Preamble – Mass, Body, Rigid Body Motion.

Definition (Body – Truesdell, 1977.)

By a body, we shall mean the closure of an open set in some measure space Ω over which a non-negative measure M, called the mass, is defined, and that M can be extended to a Borel measure over the $\sigma-$ algebra of Borel sets in Ω.

Preamble – Mass, Body, Rigid Body Motion.

Bodies – Truesdell, 1977.

That in mechanics which deals with
(i) mass points, which occupy a single point at any one time;
(ii) rigid bodies, which never deform;
(iii) strings and rods and jets, which are 1-dimensional; membranes and shells, that sweep out surfaces;
(iv) space-filling fluids and solids e.t.c. are termed bodies.

Statics, Dynamics, Rigid Body (Motion).

Statics and Dynamics

That which studies putative equilibria is referred to as statics. That which concerns motion of all sorts is referred to as dynamics. The dynamics that are specific to particular bodies are termed constitutive.

Statics, Dynamics, Rigid Body (Motion).

The Rigid Body

A rigid body does not stretch, buckle, contract, bend, twist, nor deform. Well, not really!

The Rigid Body

As engineers, we judge kinematic rigid hardware with the expectation that kinematic changes do not depart from rigid-body predictions.

Statics, Dynamics, Rigid Body (Motion).

The Rigid Body

We expect that localized stresses, active noise, vibrations and heat e.t.c will not cause reasonable departures from expectations.

Rigid Body Motion

That motion that preserves distance between all points in a body is termed a rigid body motion.

Statics, Dynamics, Rigid Body (Motion).

Rigid Body Motion

At issue are components of a rigid body's movement w.r.t to a fixed or moving frame of reference. In its most basic form, this movement is parameterized by displacement (and is sometimes time-varying e.g. for a continuum body). When solving for the movements of bodies, it is often useful to include velocities (twists) in order to characterize the motion.

Kinematics vs. Kinetics

Definition (Kinematics.)

That which describes a motion of a body is termed the kinematics. Kinematics is the English version of the word *cinématique* coined by A.M. Ampère (1775-1836), who translated it from the Greek word $k\acute{\imath}\nu\eta\mu\alpha$.

Kinematics vs. Kinetics.

Definition (Kinematics – Technical Definition)

That part of a system's dynamics that involves its motion by displacement – both linear and angular – and separated from motions owing to forces and torques, together with the successive derivatives with respect to time of all such displacements (this includes velocities, accelerations, and hyper accelerations) all form the kinematics of a rigid, continuum or laminae of bodies.

Kinematics vs. Kinetics

Kinetics

The motion of bodies can also be conceived as resulting from the forces' action. Energy, temperature, and calory of a body are resultant effects of gains or loss of heat. Motions arising as a result of these are called kinetics.

Kinematics vs. Kinetics.

Definition (Kinetics – Technical Definition)

That part of a system's dynamics that involves its motion by forces, energy, torque, inertia, dynamic stability, and equilibrium and similar properties all form the kinetics of a rigid, continuum or laminae of bodies.

Kinematic Geometry.

Definition (Kinetic Geometry)

The solid geometry of a relatively moving rigid bodies is termed the kinematic geometry of the rigid body. With motion, we'd have to include the successive derivatives of the displacement such as acceleration e.t.c as the 'laws of motion' stipulates in mechanics.