Lecture Notes

Mechanism Design and Analysis (MDA)

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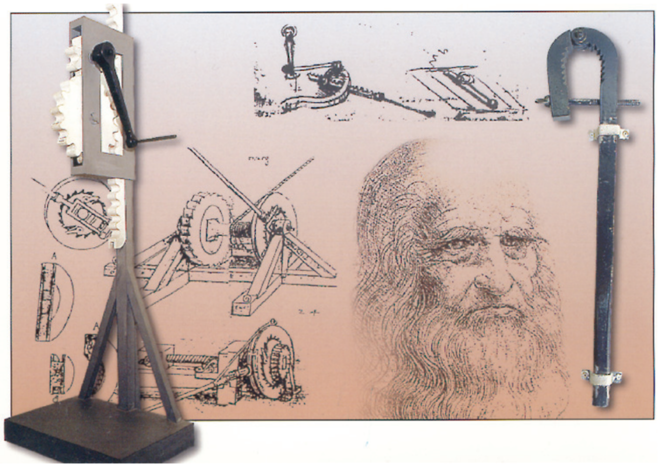
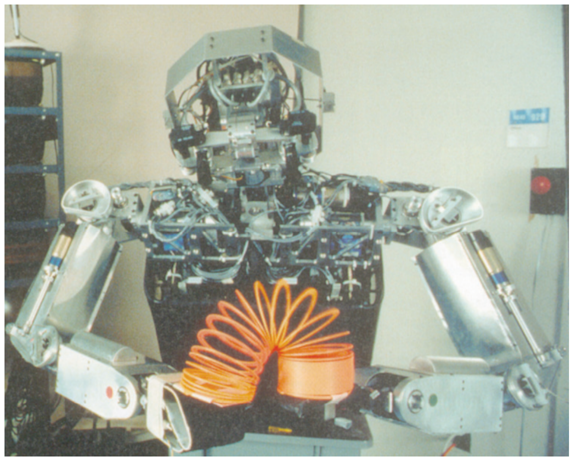
Version SS 2010 (01.03.10)

Preliminary Remarks

Mechanism design and analysis (MDA) is one of the most prominent subject of mechanical and mechatronics engineering. It is also the logical sequel to the lectures „Technische Mechanik“ in that it will now be dealt with multiple bodies in planar and spatial motion. In past and future engineers are involved in the development of sophisticated mechanisms.





Content overview

Introduction of mechanism design:

- modelling by rigid bodies and joints,
- discussion of topology as tree structures and closed loops,
- state variables and degrees of freedom (DOFs) of joints and system,
- transfer functions

Design of simple planar mechanisms, Introduction into parameter optimization

- slider crank, four-bar-mechanism

Kinematical analysis

- frames and orientation matrix,
- functions of position, velocity and acceleration,
- discussion of mechanism behaviour,
- graphical methods

Dynamical analysis

- equilibrium conditions,
- principle of virtual power,

Introduction to multibody programs

- demonstrations on examples

Goals and Objectives

Students will be able to

- understand the movement of mechanisms and to calculate the DOFs of a system

- setup the kinematical transfer functions of a planar mechanism

- calculate the applied forces and torques of the input links.

Prerequisites

Courses as Technical Mechanics I and II, Mathematics I and II, Signals and Systems, (Modelling and Simulation)

Notations

1. General variables

Scalars arbitrary letters including Greek letters, e.g. $a, b, P, x_i, \alpha, \beta, \gamma, \lambda$

Indices with letters in lower case, e.g. i, j, k, l

Matrices and vectors are lists of scalars. A vector is a column of a matrix.

Vectors are denoted by letters in lower case, for the manuscript in bold face, e.g.

$\mathbf{x} = (x_i),\ i = 1, 2, 3, \ldots, n), (x_i), i = 1, 2, 3, \ldots, n)$

for hand writing the letter is underlined, e.g. $\underline{x} = (x_i)$,

Norm $\|\mathbf{x}\| = \sqrt{x_1^2 + x_2^2 + \ldots.. + x_n^2}$

Matrices are denoted by capital letters, for the manuscript in bold face, e.g.

$\mathbf{M} = (M_{ij}),\quad i = 1, 2, 3, \ldots, n; \qquad j = 1, 2, 3, \ldots, m$

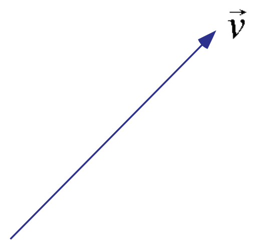
for hand writing the letter is double underlined, e.g. $\underline{\underline{M}} = (M_{ij})$

2. "Physical Vector" in space $\Re^2$ or $\Re^3$

A vector is an invariant of coordinate systems

Vectors denoted by arbitrary letters and marked by a arrow at the head, e.g.

$\vec{v}, \vec{F}$



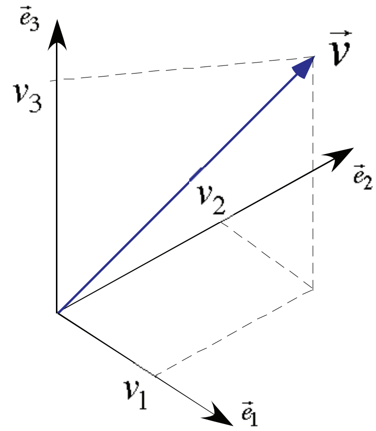
Absolute value or length or amount of the vector, e.g.

$v = |\ \vec{v}\ |; \quad F = |\ \vec{F}\ |$

3. Representation of a vector in a coordinate system (frame)

with basis vectors $\vec{e}_1, \vec{e}_2, \vec{e}_3$ (3D or 2D),

where $|\ \vec{e}_1\ | = 1$, e.g.



$$\vec{v} = \vec{e}_1\, v_1 + \vec{e}_2\, v_2 + \vec{e}_3\, v_3 \equiv \vec{\mathbf{e}}^T\, \mathbf{v} = \mathbf{v}^T\, \vec{\mathbf{e}}$$

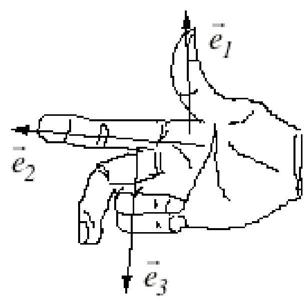
where $\mathbf{v} = (v_i) = \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix}, \quad \vec{\mathbf{e}} = (\vec{e}_i) = \begin{pmatrix} \vec{e}_1 \\ \vec{e}_2 \\ \vec{e}_3 \end{pmatrix}$

and v_1, v_2, v_3 are coordinates or components of vector $\vec{v}$.

Especially: **Cartesian right-hand frame**

$$\vec{e}_i \cdot \vec{e}_j = \delta_{ij} \quad \text{leads} \quad \vec{\mathbf{e}} \cdot \vec{\mathbf{e}}^T = \mathbf{E}$$

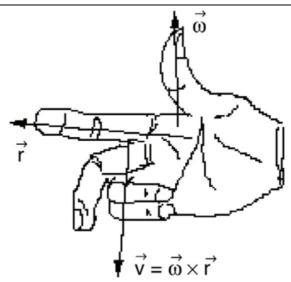
$$\vec{e}_i \times \vec{e}_j = \varepsilon_{ijk}\, \vec{e}_k \quad \text{leads} \quad \vec{\mathbf{e}} \times \vec{\mathbf{e}}^T = \begin{pmatrix} 0 & \vec{e}_3 & -\vec{e}_2 \\ -\vec{e}_3 & 0 & \vec{e}_1 \\ \vec{e}_2 & -\vec{e}_1 & 0 \end{pmatrix} = \tilde{\vec{\mathbf{e}}}^T$$



where $\mathbf{E}$ is the identity matrix, ε_{ijk} the tensor for permutation,

$\sim$ is the tilde operator w.r.t. ε_{ijk}

4. Relation between (frame independent) vectors and matrices

Vector (tensor) computations	**Matrix calculations of coordinates of vectors w.r.t. basis axes $\vec{e}_1, \vec{e}_2, \vec{e}_3$**
Vector $\vec{v}$	$\mathbf{v} = (v_i) = \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix}, \quad i = 1,2,3$
Amount (Length) $v = \lvert\vec{v}\rvert$	$v = \lvert\mathbf{v}\rvert = \sqrt{v_1^2 + v_2^2 + v_3^2}$
Addition $\vec{v} = \vec{a} + \vec{b} = \vec{b} + \vec{a}$	$\mathbf{v} = \mathbf{a} + \mathbf{b} = (a_i) + (b_i) = \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} + \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} a_1 + b_1 \\ a_2 + b_2 \\ a_3 + b_3 \end{pmatrix}$
Subtraction $\vec{v} = \vec{a} - \vec{b} = -\vec{b} + \vec{a}$	$\mathbf{v} = \mathbf{a} - \mathbf{b} = (a_i) - (b_i) = \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} - \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} a_1 - b_1 \\ a_2 - b_2 \\ a_3 - b_3 \end{pmatrix}$
Product scalar with vector $\vec{v} = \lambda\,\vec{a} = \lambda\, a\, \vec{e}_a$	$\mathbf{v} = \lambda\,\mathbf{a} = (a_i) + (b_i) = \begin{pmatrix} \lambda\, a_1 \\ \lambda\, a_2 \\ \lambda\, a_3 \end{pmatrix} = \lambda\, a \begin{pmatrix} e_{v1} \\ e_{v2} \\ e_{v3} \end{pmatrix}$
Scalar product $\mu = \vec{a}\cdot\vec{b} = \vec{b}\cdot\vec{a}$ $= a\,b\cos\angle(\vec{a},\vec{b})$	$\mu = \mathbf{a}^T\mathbf{b} = \mathbf{b}^T\mathbf{a} = a_1 b_1 + a_2 b_2 + a_3 b_3$
Cross product $\vec{v} = \vec{a}\times\vec{b} = -\vec{b}\times\vec{a}$ $v = \lvert\vec{v}\rvert = a\,b\sin\angle(\vec{a},\vec{b})$ Note: $\vec{a}\times\vec{a} = 0$	$\mathbf{v} = \tilde{\mathbf{a}}\,\mathbf{b} = -\tilde{\mathbf{b}}\,\mathbf{a}$ (also possible $\tilde{\mathbf{a}} \equiv \tilde{\mathbf{A}}$) $= \begin{pmatrix} -a_3 b_2 + a_2 b_3 \\ +a_3 b_1 - a_1 b_3 \\ -a_2 b_1 + a_1 b_2 \end{pmatrix}$ where $\tilde{\mathbf{a}} = \begin{pmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{pmatrix}$ $\tilde{\mathbf{a}}\,\mathbf{a} = \mathbf{0}, \quad \tilde{\mathbf{a}}^T = -\tilde{\mathbf{a}}$
Kinematic example $\vec{v} = \vec{\omega}\times\vec{r}$ Static example $\vec{M} = \vec{r}\times\vec{F}$	 $\mathbf{v} = \tilde{\boldsymbol{\omega}}\;\mathbf{r} = \begin{pmatrix} -\omega_z r_y + \omega_y r_z \\ +\omega_z r_x - \omega_x r_z \\ -\omega_y r_x + \omega_x r_y \end{pmatrix}$ Note $\tilde{\boldsymbol{\omega}}\tilde{\boldsymbol{\omega}} = \begin{pmatrix} -\omega_y^2 - \omega_z^2 & \omega_x\omega_y & \omega_x\omega_z \\ . & -\omega_x^2 - \omega_z^2 & \omega_y\omega_z \\ symm. & . & -\omega_x^2 - \omega_y^2 \end{pmatrix}$

Dyadic product $\vec{\vec{I}} = \vec{a} \circ \vec{b}$ = tensor type 2	$\mathbf{I} = \left(I_{ij}\right) = \mathbf{a}\,\mathbf{b}^T ,\ \mathbf{I}^T = \mathbf{b}\,\mathbf{a}^T$ $= \begin{pmatrix} I_{11} & I_{12} & I_{13} \\ I_{21} & I_{22} & I_{23} \\ I_{31} & I_{32} & I_{33} \end{pmatrix} = \begin{pmatrix} a_1 b_1 & a_1 b_2 & a_1 b_3 \\ a_2 b_1 & a_2 b_2 & a_2 b_3 \\ a_3 b_1 & a_3 b_2 & a_3 b_3 \end{pmatrix}$

5. Differentiation of Functions

Function $a(\varphi(t))$: $$\frac{da}{dt} = \dot{a} = \frac{\partial a}{\partial \varphi}\frac{d\varphi}{dt} = \frac{\partial a}{\partial \varphi}\dot{\varphi} = a'\,\dot{\varphi} = a_\varphi\,\dot{\varphi}$$

Function $a(\varphi(t),\gamma(t))$: $$\frac{da}{dt} = \dot{a} = \frac{\partial a}{\partial \varphi}\dot{\varphi} + \frac{\partial a}{\partial \gamma}\dot{\gamma} = a_\varphi\,\dot{\varphi} + a_\gamma\,\dot{\gamma}$$

6. Often used letters

K	denotes a coordinate system or frame
I	inertial frame
B	body fixed frame
R	reference frame
$\vec{e}_i$	basis vectors, $i = x, y, z$ or i,2,3; where unit vectors $\lvert \vec{e}_i] = 1$
x, y, z	frame directions of K
X,Y,Z	frame directions of inertial frame I
s, v, a	values for position, velocity and acceleration
$\alpha, \beta, \gamma, \varphi, \psi, \delta, \theta$	values for angle
ω, α	angular velocity, angular acceleration
${}^k\mathbf{r} = ({}^k r_x, {}^k r_y, {}^k r_z)^T$	coordinates of a vector w.r.t. frame k, no index denotes inertial frame 0, 1, or I.
$\mathbf{A}^{IB}$	$3 \infty 3$ orientation matrix of frame B w.r.t. I: $\vec{\mathbf{e}}_I = \mathbf{A}^{IB}\ \vec{\mathbf{e}}_B$, or ${}^I\mathbf{v} = \mathbf{A}^{IB}\ {}^B\mathbf{v}$
2D	planar motion
3D	spatial motion
2D	planar motion
3D	spatial motion
$\mathbf{E}$	identity matrix
$\mathbf{A}^T$	transposed Matrix $\mathbf{A}$; it leads to $(A_{ij})^T = (A_{ji})$
$\mathbf{A}^{-1}$	inverse matrix $\mathbf{A}$; where $\mathbf{A}^{-1}\,\mathbf{A} = \mathbf{E}$, and $\mathbf{E}$ is the identity matrix

CAD	Computer Aided Design
FEM	Finite Element Method
MBS	Multibody System
AE	algebraic equations
DE	differential equations
DAE	differential algebraic equations
DOF	Degree of Freedom

l, r, a, b, c, d, k, ..	length
e	eccentricity
0, 1, 2, 3, ...	numbers for links
12, ...	number of a joint between link 1 and link 2
$A, B,$	name of a point at links (name of a marker)
A_0, B_0, ..	name of a point at the ground

Sources and references

Recommendation References of this course

Elementary books of Mechanism Design and Analysis are (Kerle and Pittschellis 1998) or (Kerle, Pittschellis et al. 2007). An American bible is (Erdman and Sandor 1991).

Especially for German students (Jayendran 2006) and (Flack and Möllerke 1999) are proposed.

The alphabetical list follows

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Contents

1 Introduction

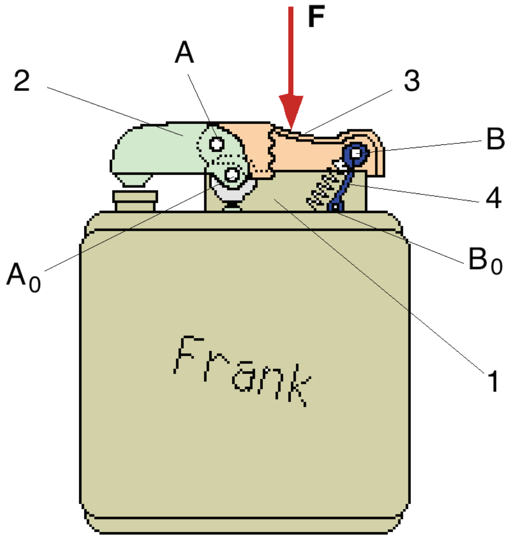
1.1 What is a Mechanism?

A mechanism is a mechanical system which **transfers motions** or **energies** from the input side to the output side.

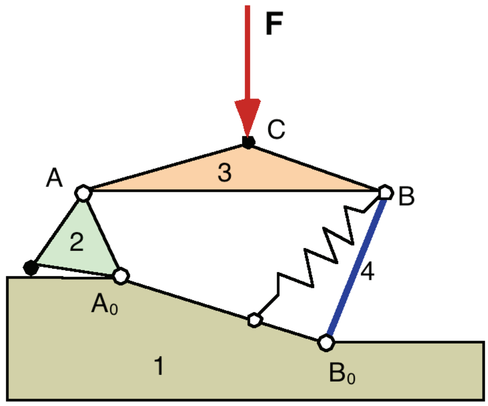
A Mechanism is an assemble of **links** (bars, bodies) which are connected by **joints** and **force elements** such as springs, dampers, actuators a.o.

Joints constrain the body motion and access their kinematics, force elements perform the body dynamics.

Example 1: Mechanism of a lighter – for transfer of energy



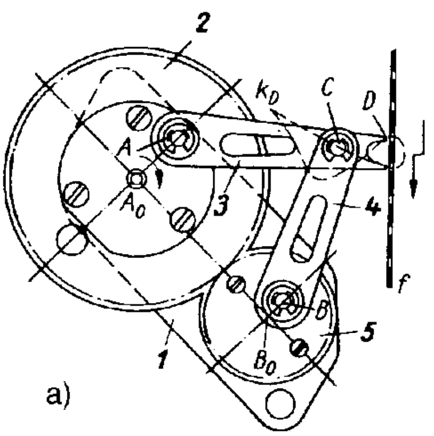
a) real construction

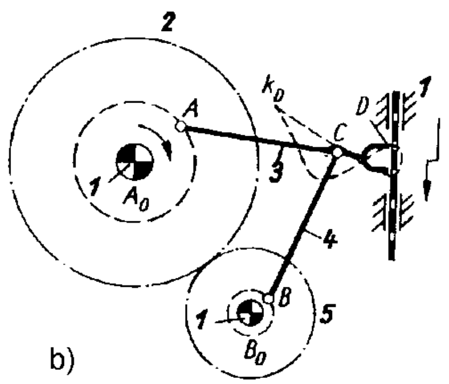


4-bar mechanism (4-bar linkage)
with 4 links (#1 = ground link)
with 4 joints (hinges at A_0, A, B, B_0)
with a spring and borders,
The system has one degree of freedom (DOF)

b) mechanism scheme

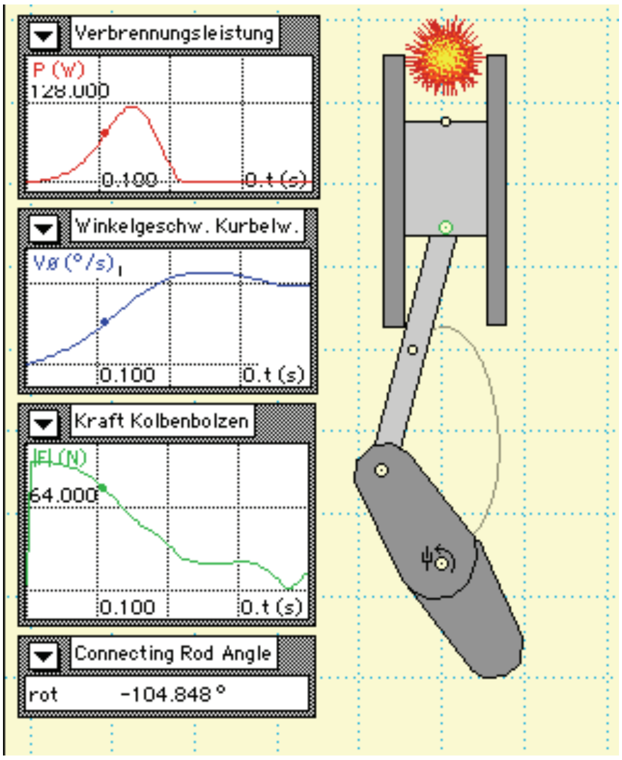
Example 2: Film transport of camera (Volmer 1989) – for transfer of motion





a) real construction **b) mechanism scheme**

Example 3: A one-cylinder engine – for transfer of energy



Exercise: Discus the mechanisms above w.r.t. joints and force elements.

Please give other examples of mechanisms.

1.2 Classification of Mechanisms

We use mechanisms with different kind of motions, but often **planar mechanisms** are applied due to the simple kind of joints such as hinges and sliders. Herein, all motions are in the plane. We call mechanisms whose axes are intersect in one point **spherical mechanisms**. All others are denoted **spatial mechanisms**.

A second classification of mechanisms is the type of **transfer function** which is referred to them.

Tables 1-1 and 1-2 from (Volmer 1989) show this behaviour.

In general, mechanisms are designed in the sense that no deformations appear in the links. We talk about **rigid bodies**. In this course, all examples are considered to be rigid. Nevertheless, all arms and links of a mechanism will be deformed due to loads and in the case of high precision machines. Then these deformations have be considered in simulations. An exaggerated example is shown in Fig. 1-4. The links are so flexible that they bend due to the gravity force.

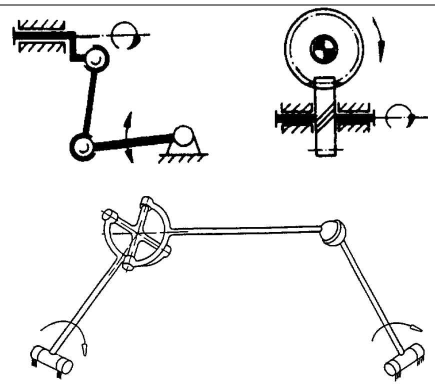
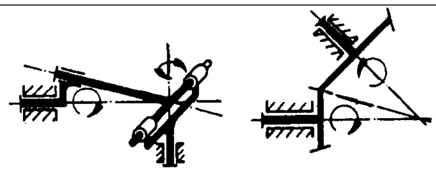
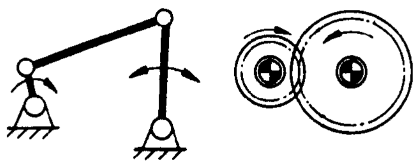
Notation	Definition	Examples
spatial mechanism	all axes are arbitrary	
spherical mechanism	all axes are crossing at one point	
planar mechanism	all axes are parallel	

Table 1-1: Mechanisms with different motions in space.

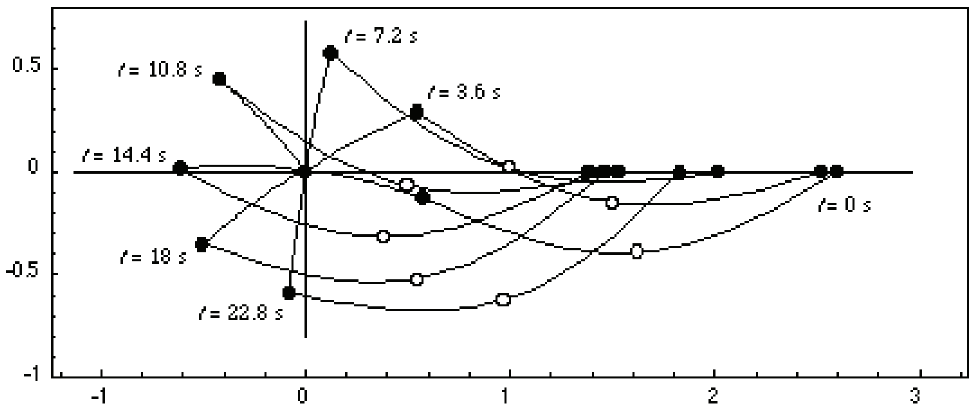


Fig. 1-4: Example of a slider-crank mechanism with flexible crank and coupler (Schwertassek and Wallrapp 1999).

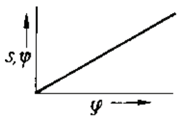
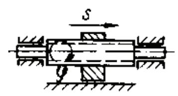
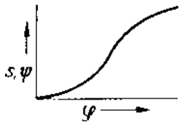
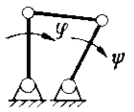
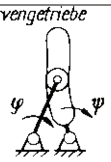
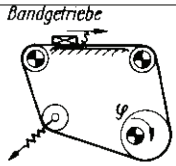
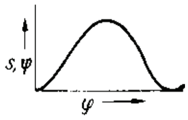
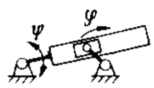
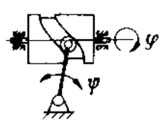
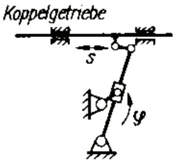
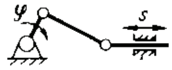
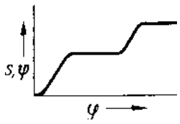
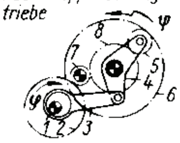
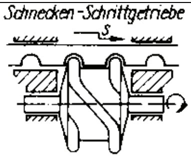
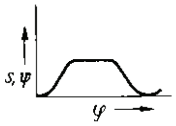
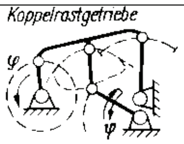
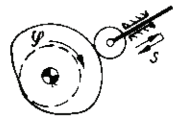
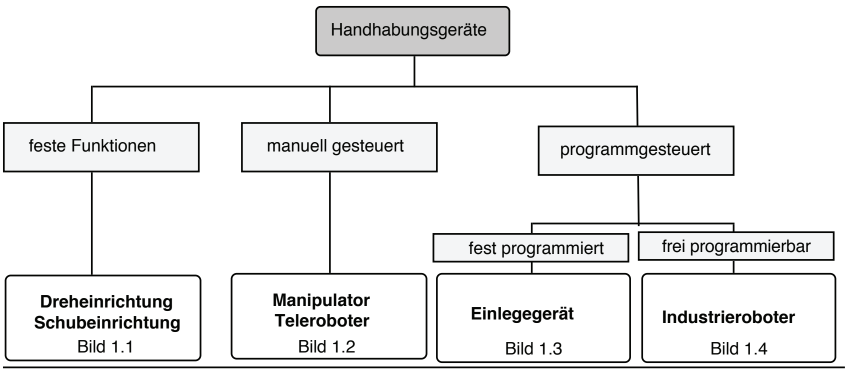
Transfer function	*Graph of transfer*	*Examples*		
constant		Gear mech Zahnrädergetriebe 	Parallelkurbelgetriebe 	Screw spindle mech Schraubengetriebe 
arbitrary, continuously		Double crank mech Doppelkurbel 	Kurvengetriebe 	Bandgetriebe 
arbitrary, oscillating		Crank rocker mech Kurbelschwinge  Crank shaper mech Kurbelschleife 	Kurvengetriebe  Koppelgetriebe 	Slider crank mech Schubkurbel 
arbitrary, continuously, with dwell		Malteserkreuzgetriebe 	Räder-Koppel-Schrittgetriebe 	Schnecken-Schrittgetriebe 
arbitrary, oscillating, with rise, dwell, fall		Koppelrastgetriebe 		Cam system with cam shaft & follower Kurvengetriebe 

Table 1-2: Mechanism's classifiation w.r.t the transfer function.

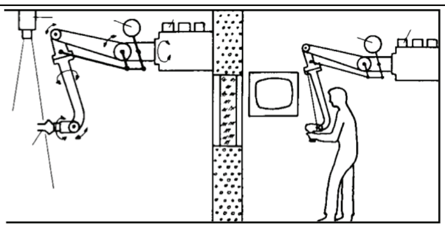
Note: Gear mechanisms with non-circular wheels are also possible, see section 1.4.

A third classification of mechanisms is related to the applications. Many machines are in use in manufacturing and assembly processes. Referring to (VDI-2860 1990) Fig. 1-5 gives an overview; Fig. 1-6 shows some examples.

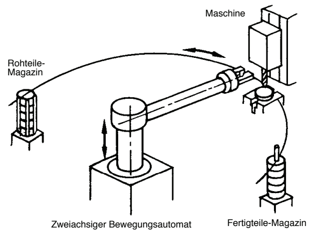


fixed function manually controlled fixed programme freely

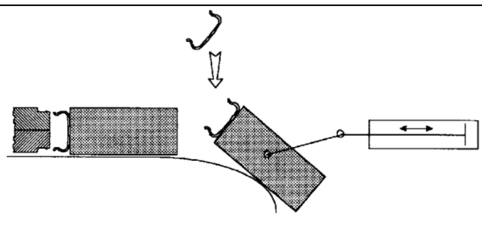
Fig. 1-5: Machines and apparates for manufacturing and assembly processes.



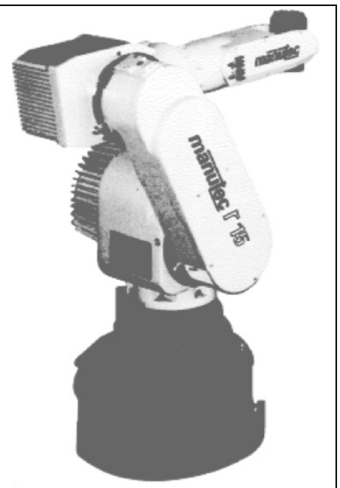
Mechanism to press in cramps



Pick and place application



Master-Slave Manipulator

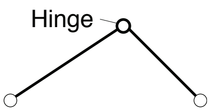


6-Axes-Robot

Fig. 1-6: Some examples of manufacturing and assembly machines.

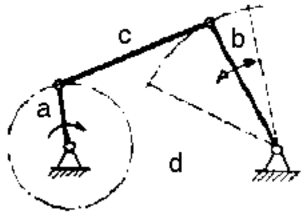
1.3 Elementary Mechanisms

The lowest elementary mechanism is a couple of links connected by a joint like a hinge: the 2-bar-linkage.

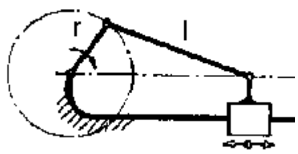


The following possible mechanisms are a combination of two 2-bar-linkages leading a 4-bar-linkage having 4 linkages and 4 joints. We get several elementary mechanisms:

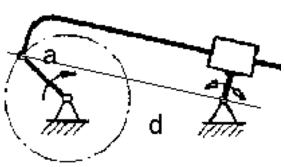
- the crank-rocker mechanism



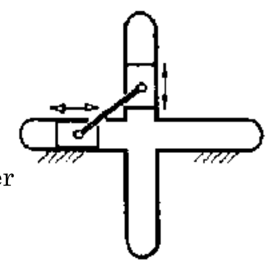
- slider-crank mechanism with 4 links, 3 hinges and 1 slider



- crank-shaper mechanism with 4 links, 3 hinges and 1 slider



- elliptic-trammel mechanism with 4 links, 2 hinges and 2 slider

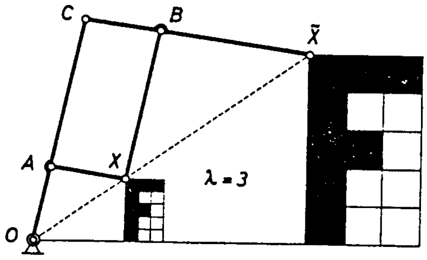


All other mechanisms are extensions of these elementary mechanisms added by 2-bar-linkages.

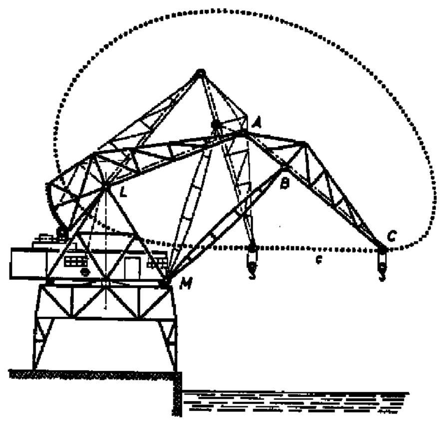
1.4 Mechanisms with Specific Functions

This section shows some mechanisms having specific transfer functions.

Pantograph (transfer ratio l = line OC with respect to line OA)



A crane with a straight line motion of the path tracer point C, realised with a 4-bar mechanism



Gear wheel pairs with non-circular wheels having a non-linear transfer function

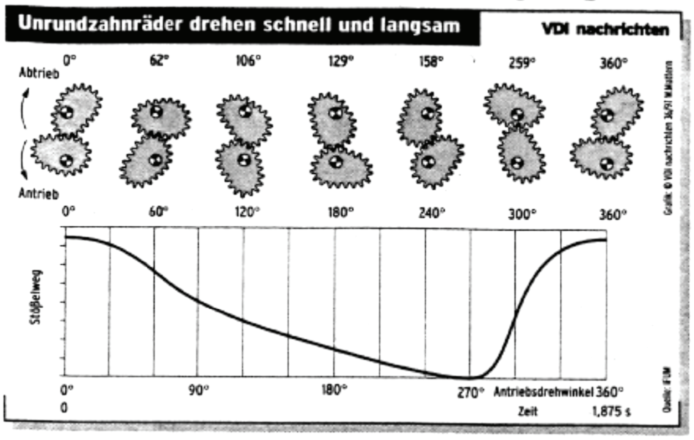
ZUM THEMA

Unrund-Zahnräder flexibilisieren die Stößelbewegung

Der Prototyp, der am Institut für Umformtechnik und Umformmaschinen an der Universität Hannover den Dauerbelastungstest bestanden hat, war ursprünglich eine normale Exzenterpresse mit einer Nennkraft von 2000 kN. Inzwischen ist die Presse um ein unrundes Zahnradpaar mit Evolventenverzahnung erweitert worden. Je 59 Zähne vom Modul 10 mm übersetzen den Antrieb. Die beiden Zahnräder sind 15 cm dick und 70 cm breit.

Die Presse-Kinematik wird durch die unrunden Räder so verändert, daß das Werkzeug langsam auf das Werkstück aufsetzt und es gleichbleibend langsam umformt. Im Vergleich zu anderen Pressen setzt die unrunde Presse bei gleicher Hubzahl dreimal langsamer auf dem Werkstück auf. Damit ist sie gut zum Tiefziehen geeignet und durch die im Verhältnis höhere Produktivität auch aus wirtschaftlicher Sicht vorbildlich.

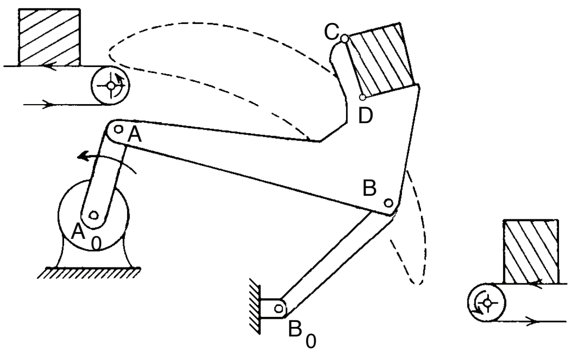
Die Steigerung des Nennkraft-Stößelweges gibt das IFUM mit rund 250 % an. Das Antriebsmoment, bei dem die Stößelnennkraft erreicht wird, verringert sich beim Antrieb mit unrunden Zahnrädern. Pressen könnten mit dem neuen Antrieb also kleiner und kostengünstiger ausgelegt werden.



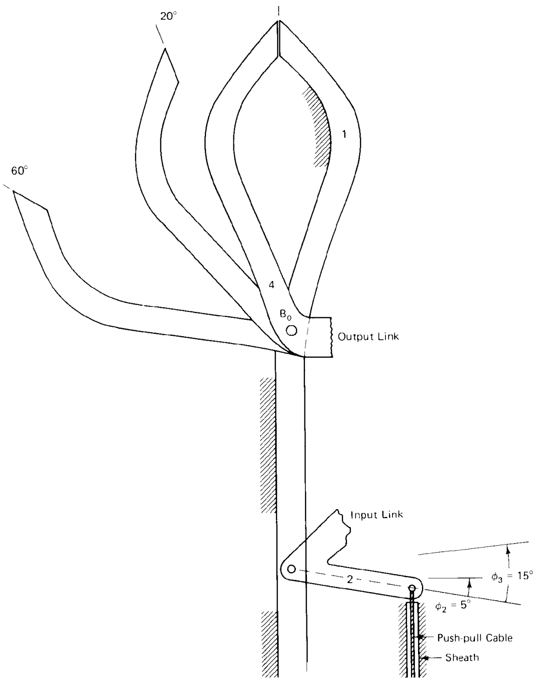
Zuordnung von Zahnradstellungen und Stößelweg: Bei gleichen Antriebsdrehwinkel-Intervallen dreht das Abtriebszahnrad in verschiedenen Schritten weiter. Durch den nachgeordneten Kurbeltrieb entsteht die in der unteren Bildhälfte gezeigte Stößelbewegung beim Tiefziehen.

Und noch einen Vorteil sehen die Ingenieure: Gelenkpressen, die sonst bei ungewöhnlichen Anforderungen an die Stößelkinematik eingesetzt werden, können immer nur für einen Verlauf konzipiert werden, die unrunden Antriebe dagegen sind flexibel. Verändert sich der gewünschte Stößelhub, müssen lediglich neue, entsprechend veränderte Zahnräder in die Presse eingebaut werden. För/Käm

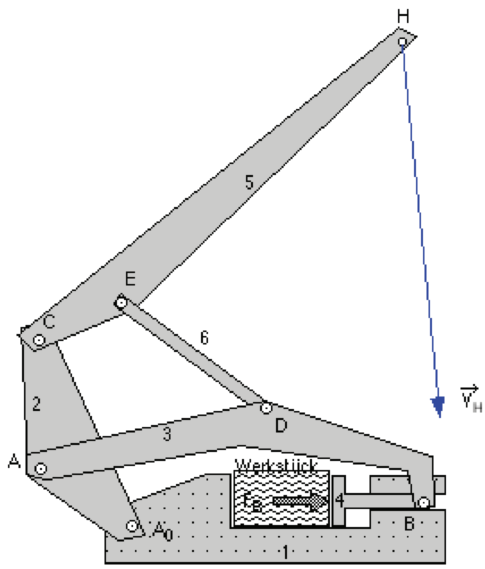
Handling machinery:
"Find all the link's lengths that are needed to take a box from the right side, turn it by 90° and put it down at the left side."



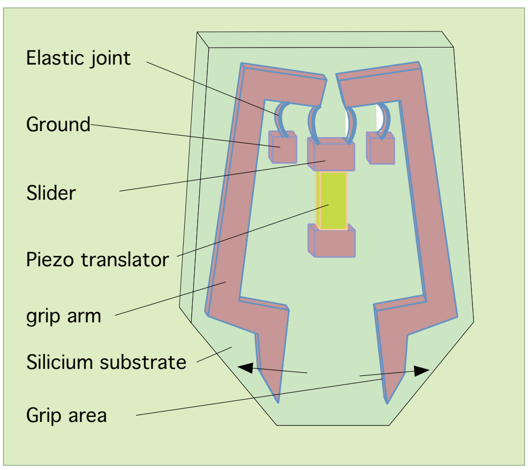
Gripper: "Find the linkages for the given input and output"

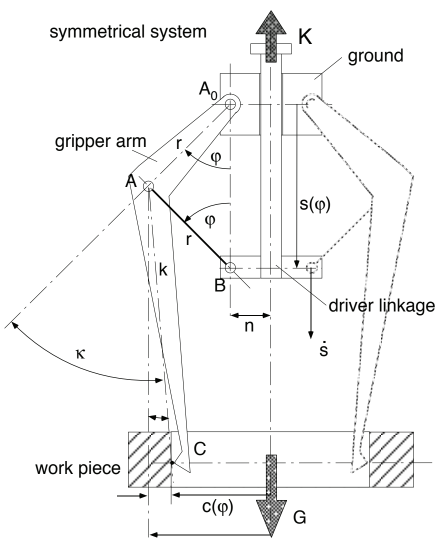


Pressure machinery

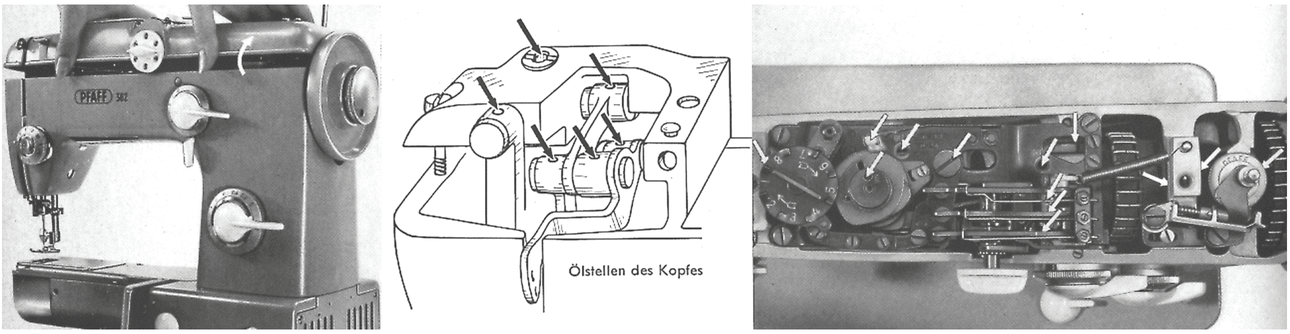


Micro gripper produced by Silicon

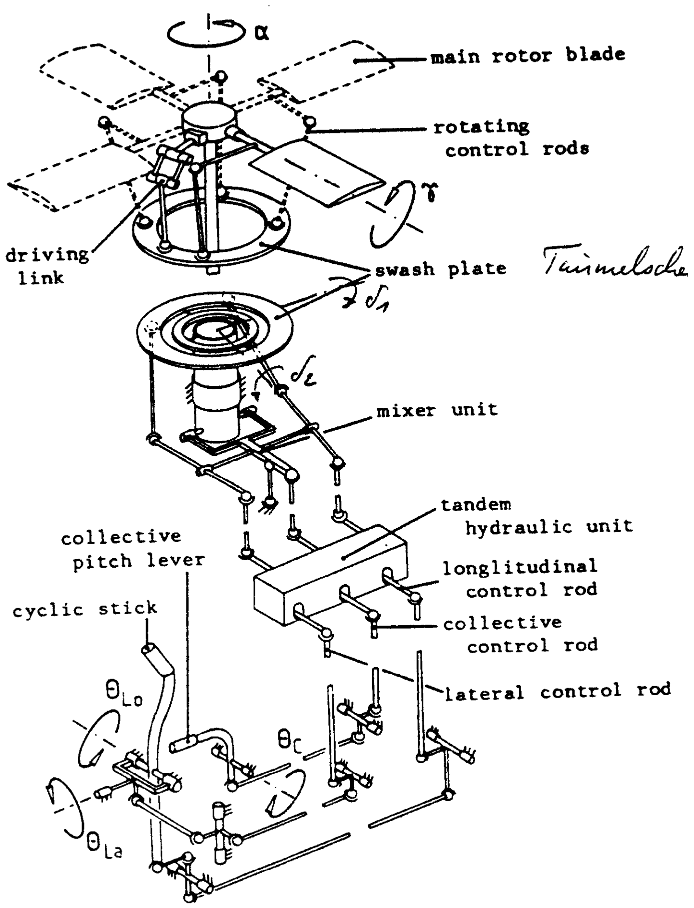




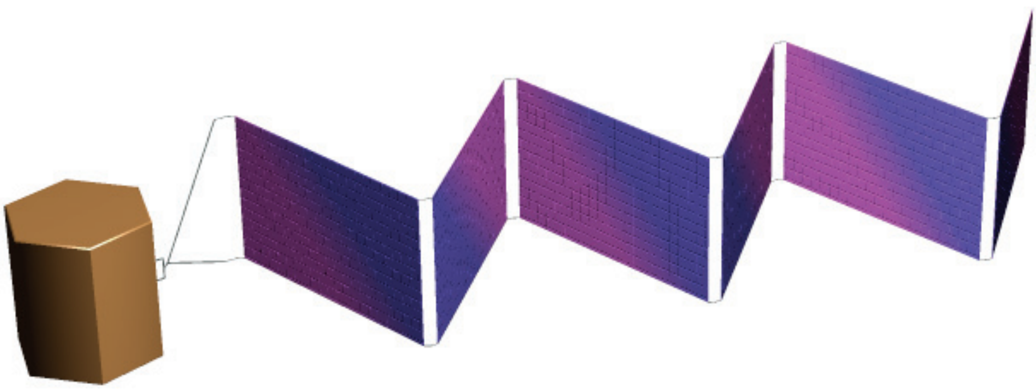
Sewing machine



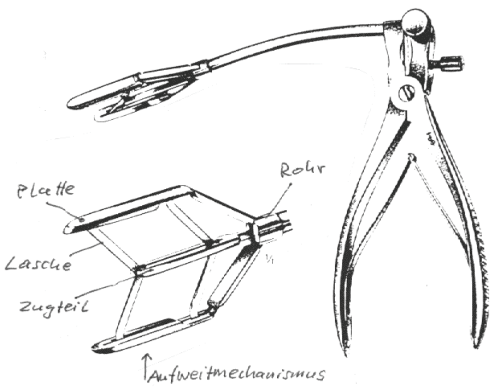
Control unit of helicopter rotor blades (43 links, 4 DOFs)

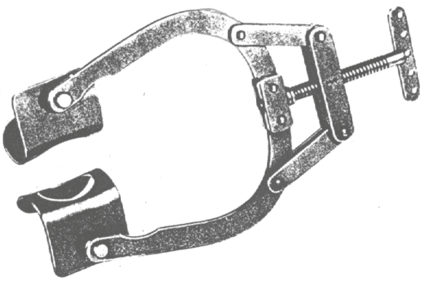


Satellite with flexible yoke and 6 flexible panels (Wiedemann 1999).

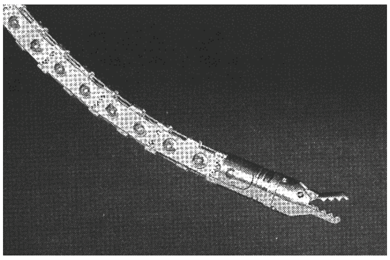


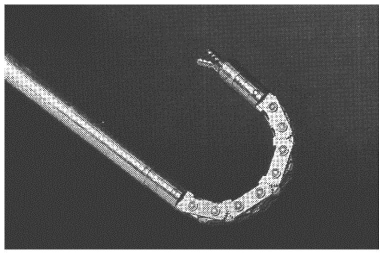
Surgical tools using for dilating valves.



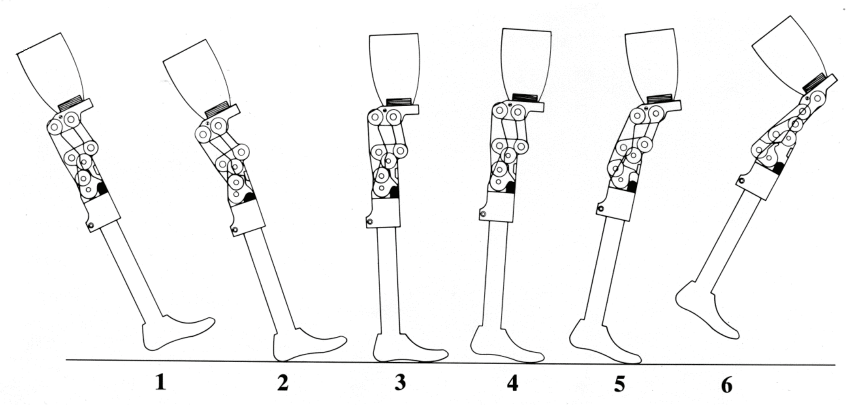


Surgical tools for the Minimal-Invasive-Surgery

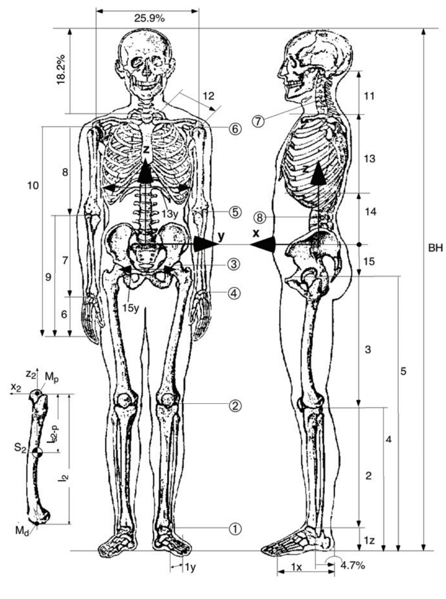




Prosthetic knee mechanism (sketches for different walking positions)



The human body modelled as a mechanical system, see the course Biomechanics



1.5 Methods for the Analysis and Design of Mechanisms

We distinguish between **Design (**or **Synthesis)** and **Analysis**.

In the design, there is a idea of desired motion or energy flow and we want to find a machine which realise this idea. This question is often a significant process of engineering.

Second, there is a machine in form of a real system, a physical scaled model or a drawn model and we want to know, how does it works or what facts of motion it has. These process of engineering is called analysis of a machine. Tab. 1-3 summarises these statements. An overview of related programs is given in Tab. 1-4.

Given	***Wanted***	***Method***
Design or Synthesis Motion of a path tracer point or a plane due to a given input motion	Required mechanism with length and angles of all links, as well as type of joints.	Synthesis of mechanisms, CAD, Parameter optimisation
Analysis of Kinematics Mechanism with motion of the input link	Rigid body motion of all other links and path tracer points, transfer function.	Theory of mechanisms, Multibody Dynamics (rigid bodies) *Modelling and Simulation*
Analysis of Dynamics Mechanism with motion of the input link as well as loads at all links	Required input force or torque, force and torques at joints (constraint forces) in addition to the motion of all other links and path tracer points, transfer function.	Theory of mechanisms, Multibody Dynamics (with only rigid bodies) *Modelling and Simulation*
Analysis of Deformation Mechanism with motion of the input link as well as loads at all links	Deformations, stress and strain of selected links during motion	Continuum mechanics, Finite element method, Multibody Dynamics (with flexible bodies) *Modelling and Simulation*

Table 1-3: Methods in analysis and design of mechanisms

Specific Mechanism Programs:

Program *Approx for Windows* (Stauchmann 2002);
see authors home page http://www.fh-muenchen.de/fb06/professoren/wallrapp/d_wallrapp_o.html

General Purpose Programs

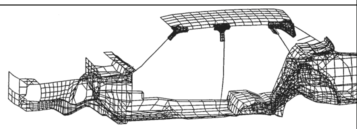
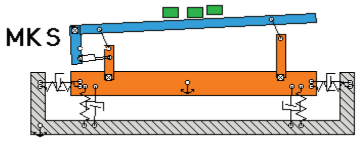
Topic	**CAD**	**FEM**	**MBS**
=			
			
Used for	Design of system, set-up data for geometry and material	Computation of strains and stresses due to loads	Computation of the nonlinear kinematics and dynamics of mechanical systems with rigid bodies
Options	analysis of kinematics, possibilities of synthesis FE-net generation	nonlinear kinematics and dynamics, Preparation of data for MBS	add flexible bodies, stress evaluation
Programs	Catia, Euklid Pro-Engineer, AutoCAD, Solid Edge Solid Works	ANSYS, ABAQUS, MARC, Nastran see (Brebbia 1982)	ADAMS, DADS, SIMPACK, WorkingModel ReCurDyn see (Schiehlen 1993), (Kortüm, Sharp et al. 1993)

Table 1-4: Programs for the Analysis and Design of Mechanisms