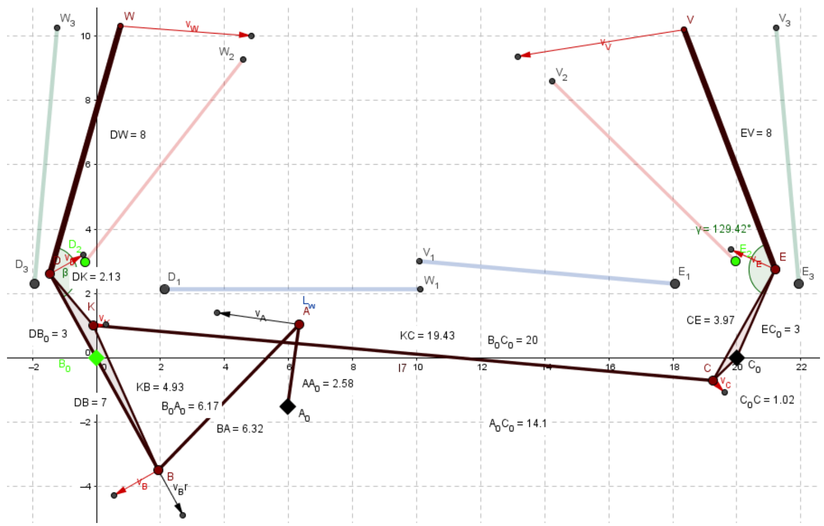
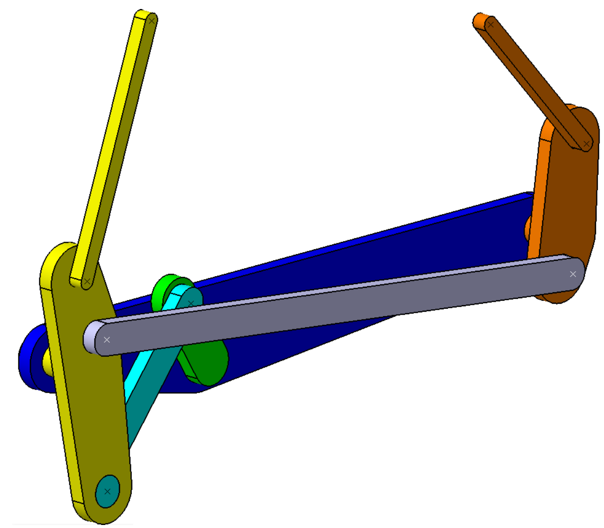
Isabel PRAUSE [a]
Jean-Christophe.FAUROUX@ifma.fr [b]
Mathias HÜSING [a]
Burkhard CORVES [a]

Using Geometry Sketchers & CAD Tools for Mechanism Synthesis

[a] IGM | RWTH AACHEN UNIVERSITY

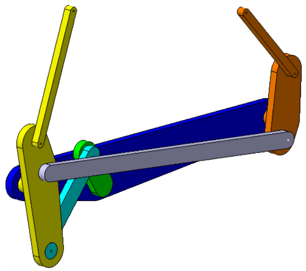
[b] IFMA INSTITUT FRANÇAIS DE MÉCANIQUE AVANCÉE · INSTITUT PASCAL





IFToMM 2015 TAIPEI

The 14th IFToMM World Congress
Date : Oct. 25-30, 2015 / Venue: Taipei International Convention Center, Taiwan



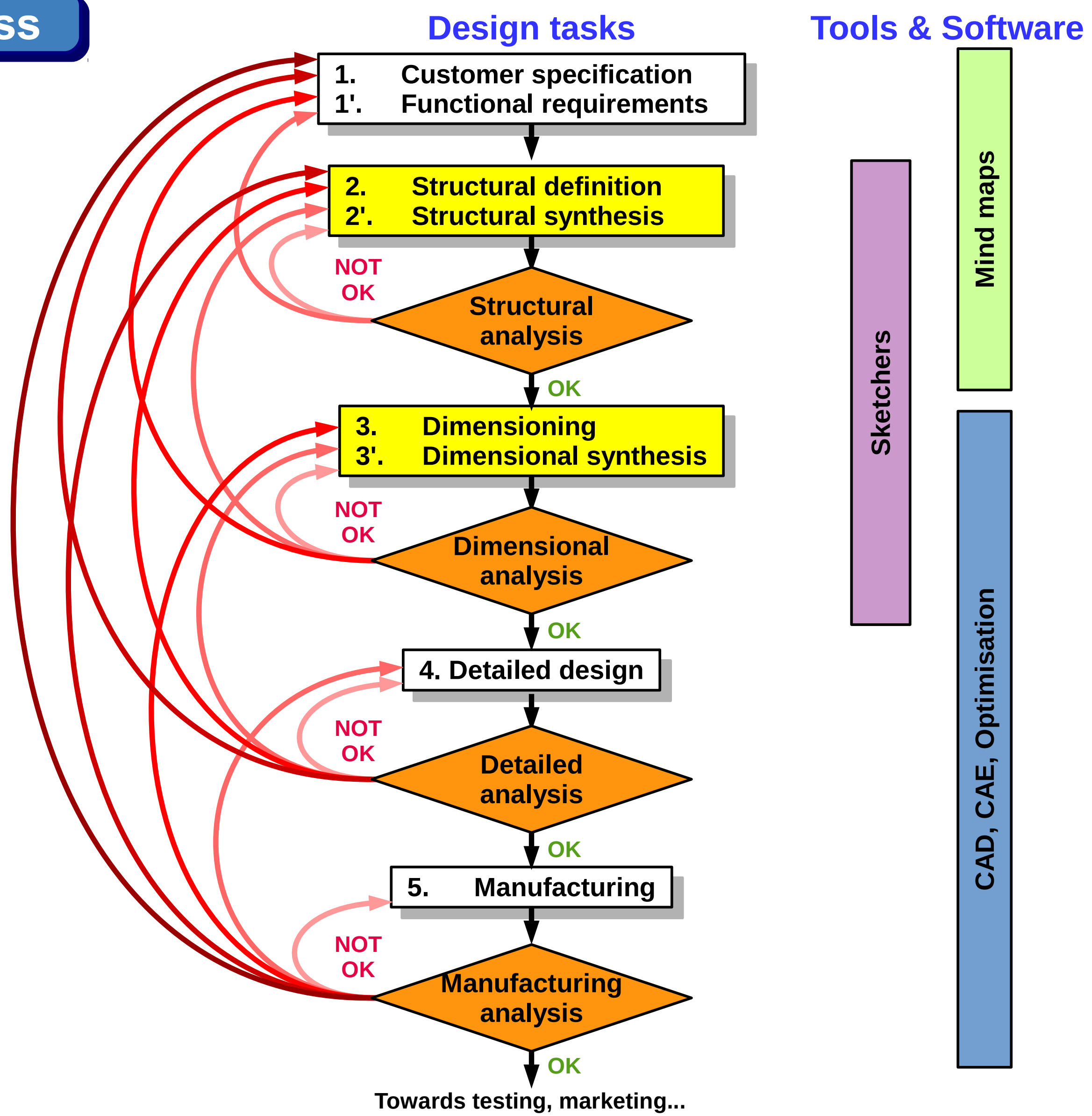
Synthesis into the design process

Geometric tools for synthesis

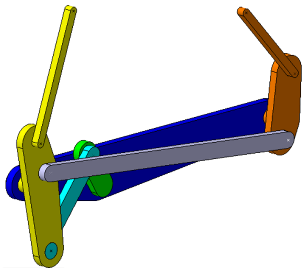
- Tools for design
  - Design proc.
  - CAD
  - IGS
- Synthesis
- Applications
- Conclusion

Design process

- **Synthesis**: structural and dimensional
- **Iterative** process
- **Sketchers** could possibly cover structural & dimensional synthesis
- **CAD tools** represent the product in a more detailed form
- This paper focuses on **dimensional synthesis**
- Comparison **Sketchers vs. CAD**



PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard



Existing software for mechanism design

Geometric tools for synthesis

- Tools for design
  - Design proc.
  - CAD
  - IGS
- Synthesis
- Applications
- Conclusion

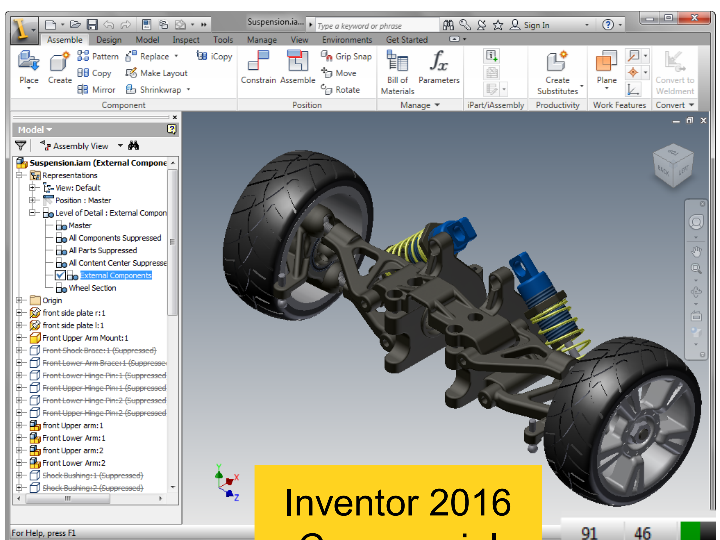
CAD (Computer Aided Design)

- Constructive Solid Geometry (**CSG**)
- Boundary representation (**B-Rep**)
- **Parametrized** models
- **Variational** models (constraint based)

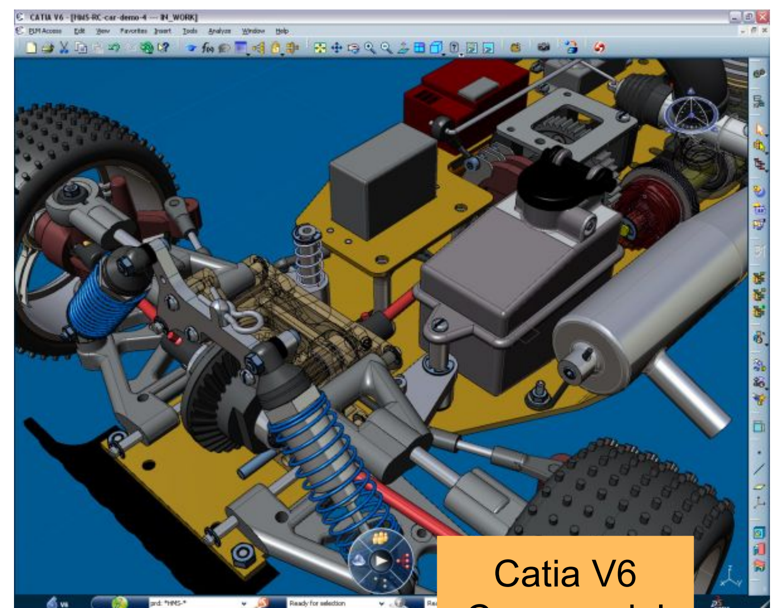
- Geometry (2D sketches, volumes, surfaces)
- Drafting
- Assembly
- Kinematics
- Milling (3 and 5 axes)
- Sheet metal
- Cable harness
- Virtual reality

Examples of CAD software for SMEs
Solidworks www.solidworks.fr
SolidEdge www.plmautomation.siemens.com
Think3 www.think3.eu

Examples of CAD software for big groups
Catia www.3ds.com/fr/produits-et-services/catia
Creo www.ptc.com/product/creo
Inventor www.autodesk.fr/products/inventor
NX www.plm.automation.siemens.com/fr_fr/products/nx

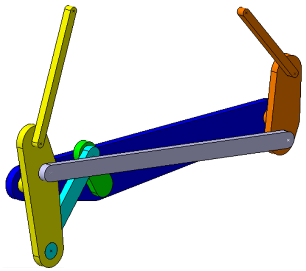


Inventor 2016
Commercial



Catia V6
Commercial

PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard

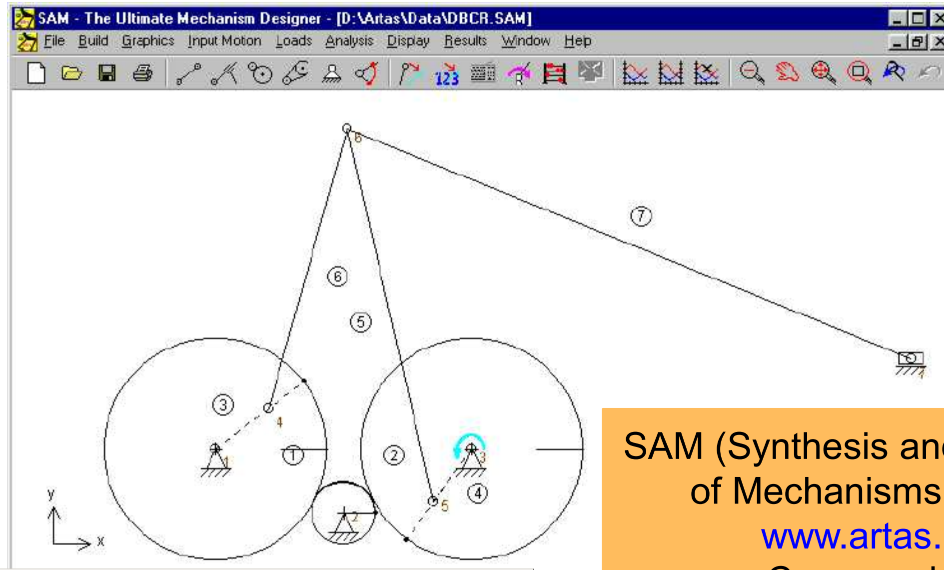


Existing software for machine design

Special software for machine design

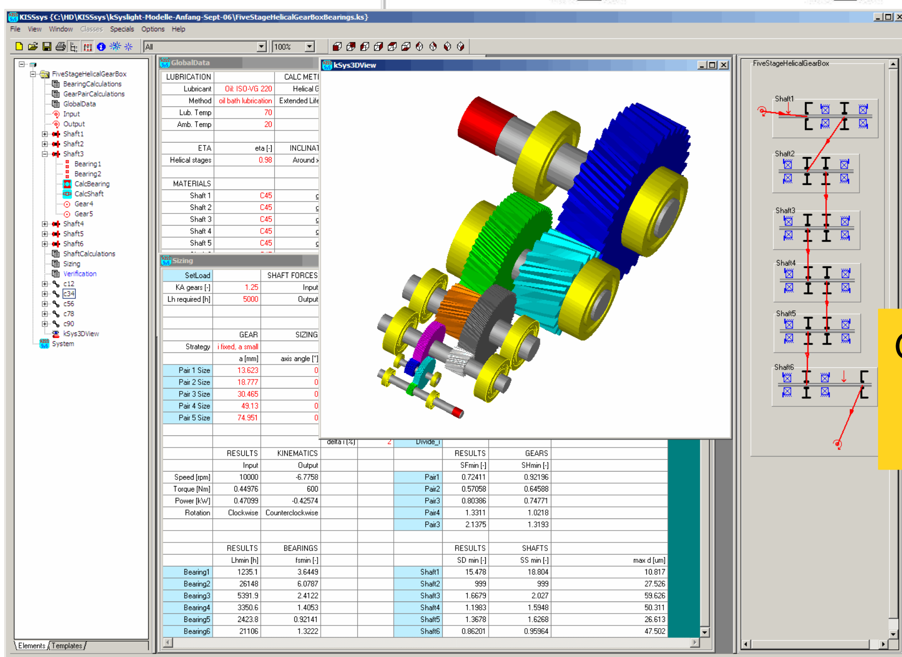
Geometric tools for synthesis

- Tools for design
  - Design proc.
  - CAD
  - IGS
- Synthesis
- Applications
- Conclusion



SAM (Synthesis and Analysis of Mechanisms) V7.0
www.artas.nl
Commercial

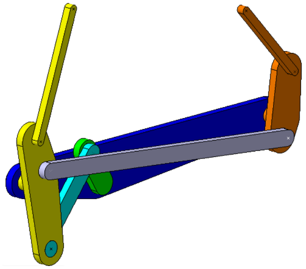
- Linkages
- Transmissions
- Analysis
- Optimisation



GPK gearbox package
www.kissoft.ch
Commercial

- Sizing, optimization and rating of gearboxes
- Dimensioning of elements: gears, shafts, bearings, springs, belts

PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard



Existing software for machine design

Geometric tools for synthesis

- Tools for design
  - Design proc.
  - CAD
  - IGS
- Synthesis
- Applications
- Conclusion

Multibody simulation

- Rigid bodies, Joints
- Kinematics & dynamics
- Iterative solving of dynamics differential equation
- Parametrizing, Optimization
- Flexible bodies → Extension to FEM

Examples of multibody software

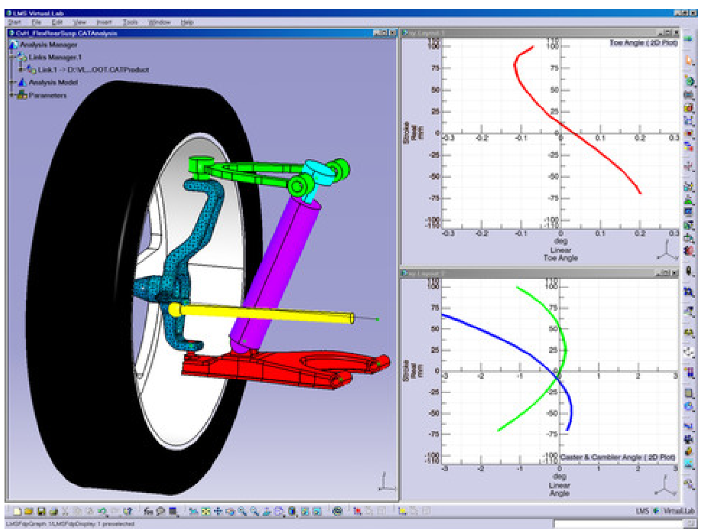
Adams www.mscsoftware.com/fr/product/adams

LMS Virtual Lab Motion www.plm.automation.siemens.com/fr_fr/products/lms/virtual-lab/motion/index.shtml

Simpack www.simpack.com

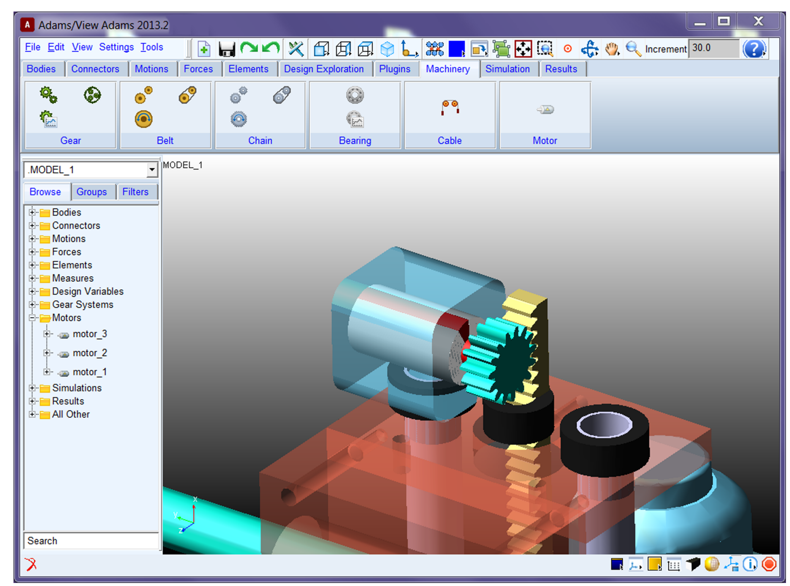
Open Dynamic Engine www.ode.org

Gazebo http://gazebosim.org



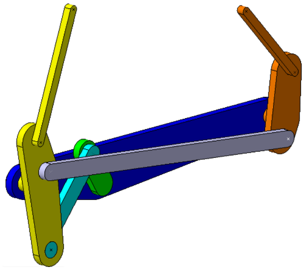
LMS Virtual Lab Motion
Commercial

MSC Adams 2015
Commercial



PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard

Existing software for mechanism design

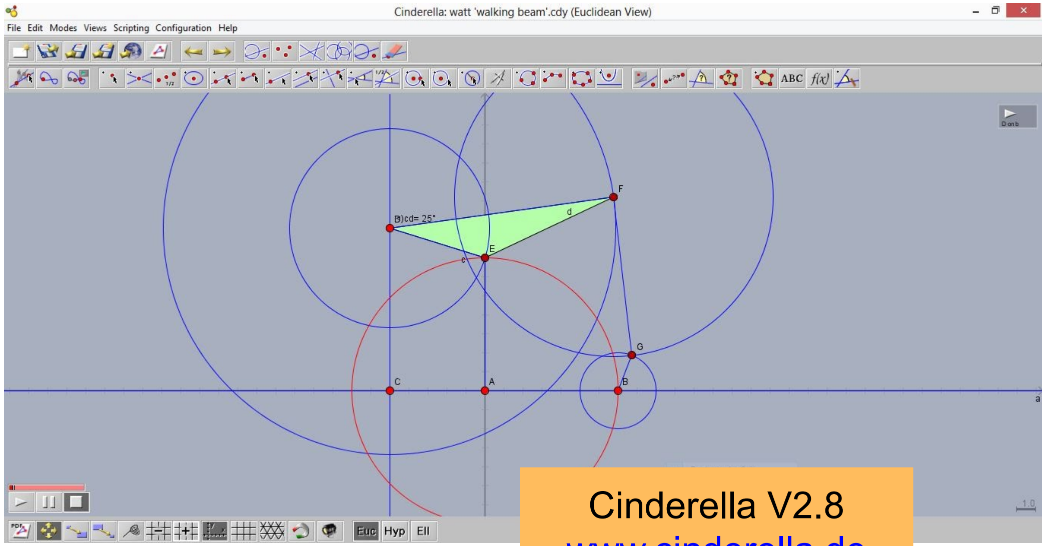


Geometric tools for synthesis

- Tools for design
  - Design proc.
  - CAD
  - IGS
- Synthesis
- Applications
- Conclusion

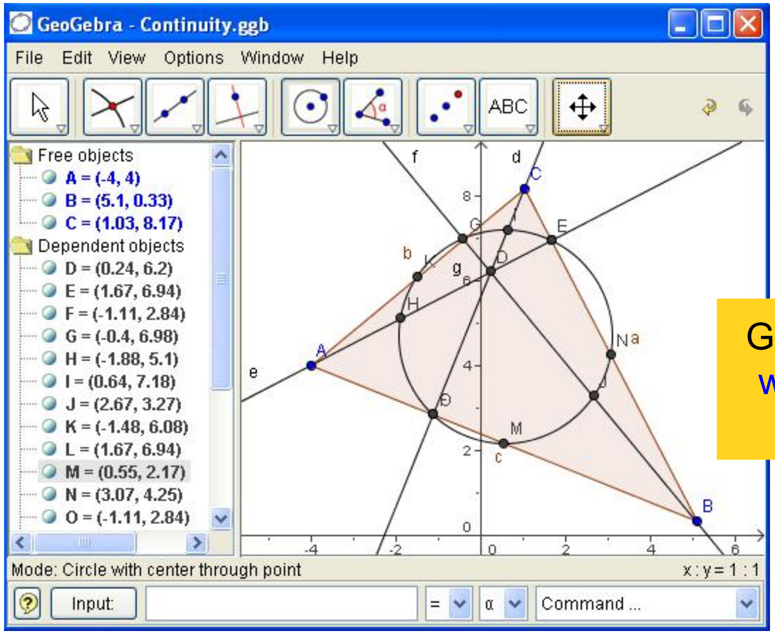
Interactive Geometry Software (IGS)

2 representative solutions:
- Java implementation
- Linux / MacOS / Windows



Cinderella V2.8
www.cinderella.de
Free, since 1998

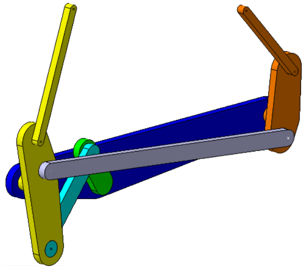
- Euclidean, spherical & hyperbolic geometry
- Physics simulation
- Scripting & algorithms



GeoGebra V5.0.166
www.geogebra.org
Free, since 2001

- 2D / 3D geometry
- Algebraic expressions
- Symbolic calculation
- Spreadsheet
- Parametrization / scenarios

PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard



Interactive Geometry Software (IGS)

Geometric tools for synthesis

- Tools for design
  - Design proc.
  - CAD
  - IGS
- Synthesis
- Applications
- Conclusion

Main functions

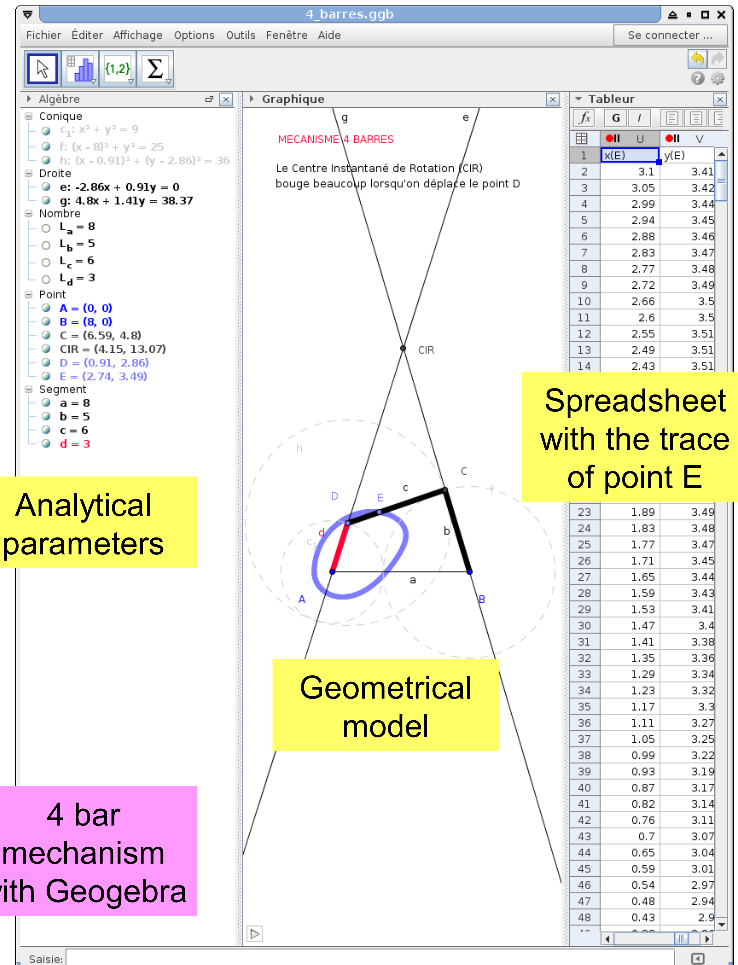
- Sketching in 2D/3D as with a ruler and compass
- Parametrization
- Simple constraints (point on curve) but not really variational

IGS vs. Paper work

- Precision
- Parametrization for *a posteriori* modification
- Sequential process that can be replayed

Designing with mechanism skeletons

- **Mechanism skeleton**: simplified product representation for synthesis at a higher lever of abstraction
- **Skeleton in CAD**: group of reference geometrical entities (points, lines, planes) required to reconstruct a shape by a self-coherent process
- Using a skeleton **minimizes reconstruction problems** due to referencing features that do not exist any more within the current set of parameters.



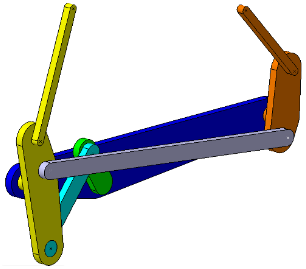
Analytical parameters

Spreadsheet with the trace of point E

Geometrical model

4 bar mechanism with Geogebra

PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard



Synthesis 1: Three position synthesis (1/2)

[Mallik 94]
[McCarthy11]
[Uicker 11]

Notations

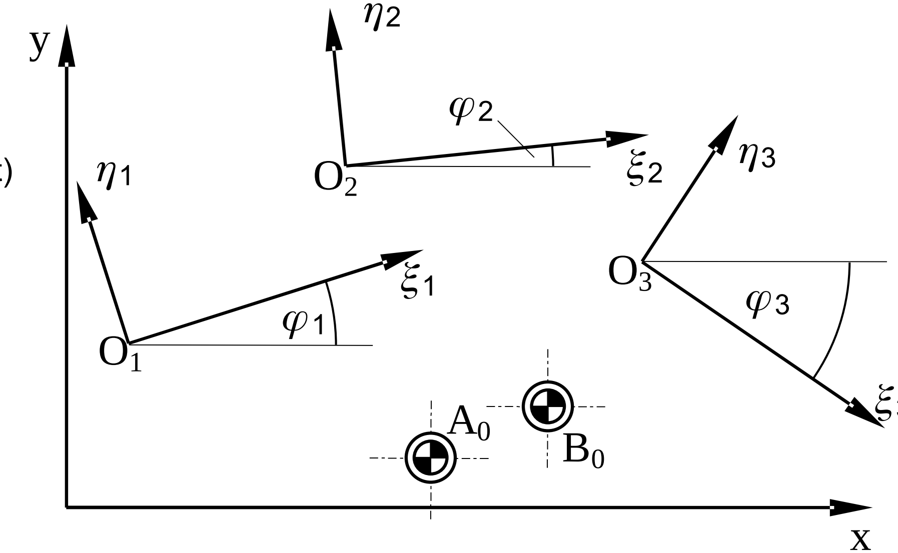
- A_0: rot. point of the crank (frame joint)
- B_0: rot. point of the rocker (frame joint)
- A: coupling joint crank-coupler
- B: coupling joint coupler-rocker

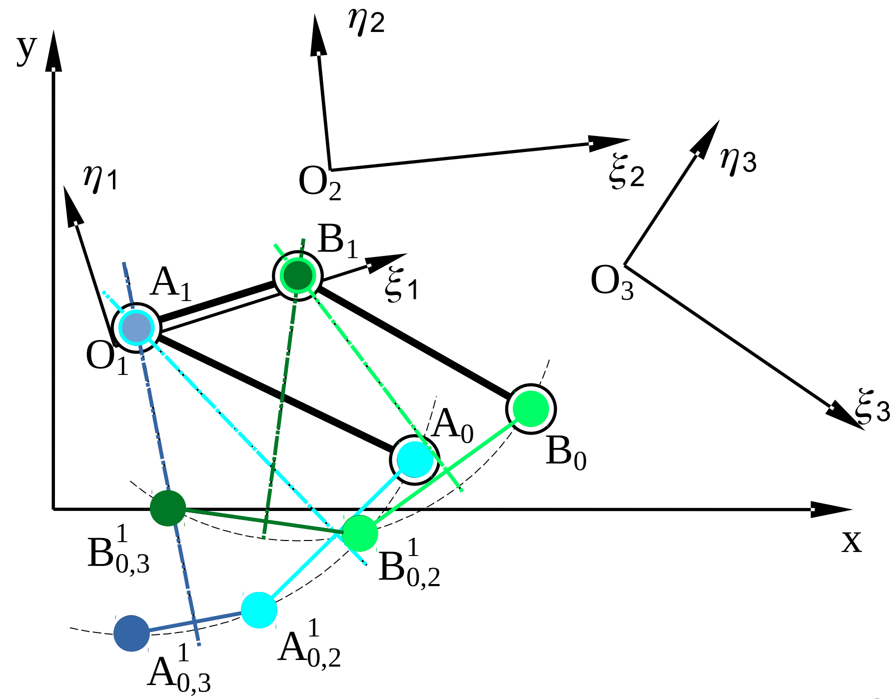
Problem setting

- Given A_0 and B_0
- Given 3 poses of the coupler…
- ...Find A and B positions

Algorithm

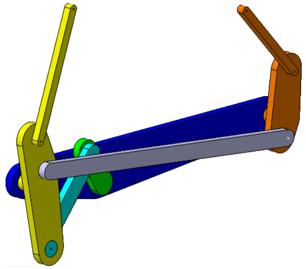
- $A^1_{0,3} = A_0$ *transferred* from pose 3 to 1
- $A^1_{0,2} = A_0$ *transferred* from pose 2 to 1
- A_1 = *intersection* (
  (*right_bisector* $(A^1_{0,2}, A^1_{0,3})$,
  (*right_bisector* $(A^1_{0,2}, A_0)$)
- $B^1_{0,3} = B_0$ *transferred* from pose 3 to 1
- $B^1_{0,2} = B_0$ *transferred* from pose 2 to 1
- B_1 = *intersection* (
  (*right_bisector* $(B^1_{0,2}, B^1_{0,3})$,
  (*right_bisector* $(B^1_{0,2}, B_0)$)





Geometric tools for synthesis

PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard



Synthesis 1: Three position synthesis (2/2)

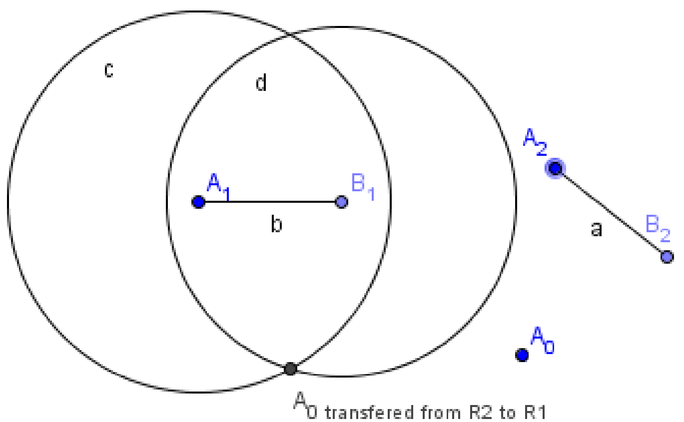
Geometric tools for synthesis

- Tools for design
- Synthesis
  - 3 position
  - Dead Center
  - Roberts-Cheb.
- Applications
- Conclusion

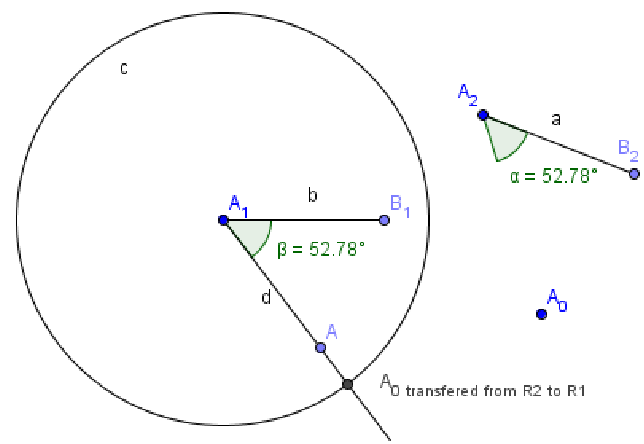
Transferring a point

- P^i_j : point that has a relative position in frame i identical to the relative position of P in frame j
- Manually, can be performed with transparent paper
- With an IGS, similar to a sub-routine

Sub-Routine 1: Circle intersections

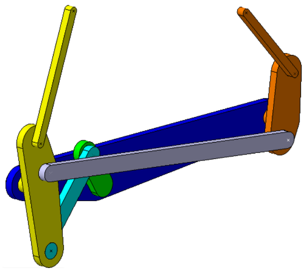


Sub-Routine 2: Angle measure



- Sub-routine 1 is less robust because the intersection of two circles gives two points → branching

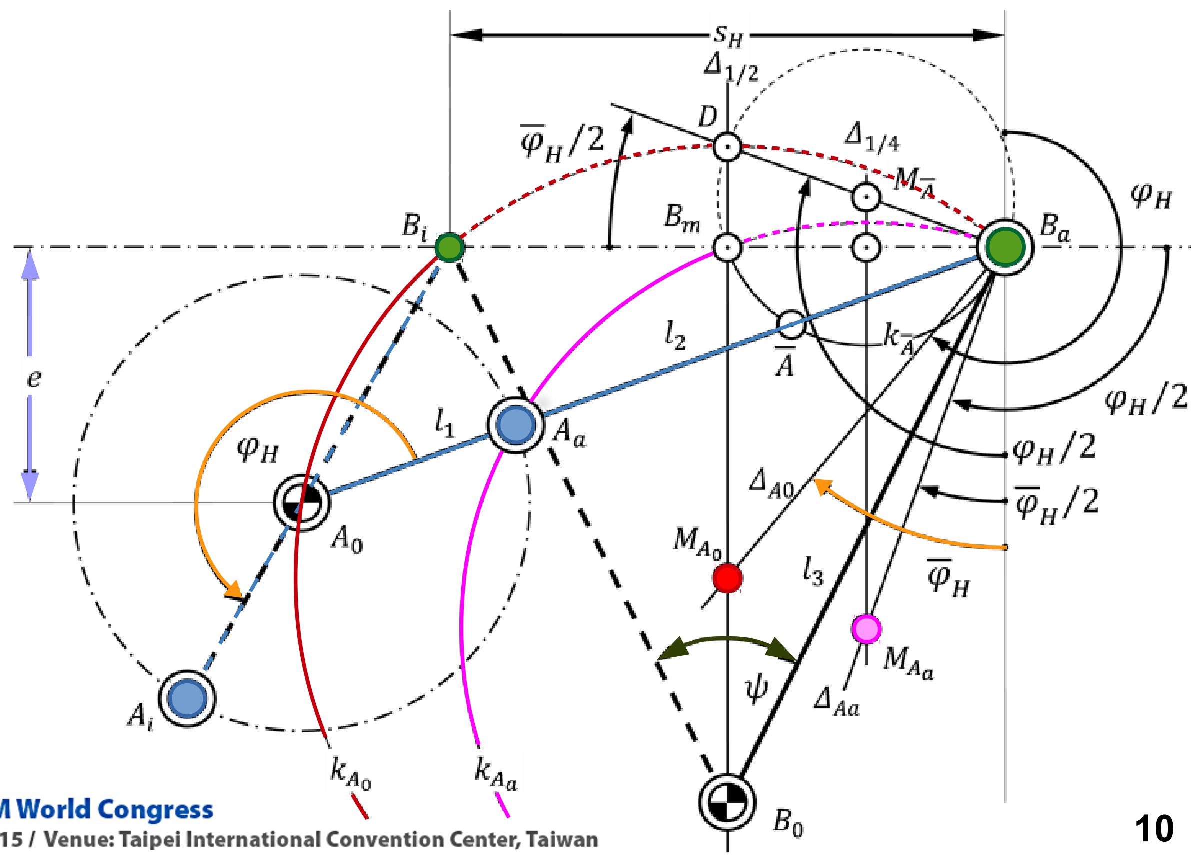
PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard



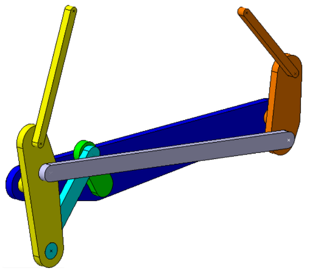
Synthesis 2: Dead center position synthesis

Notations

- A_i / A_a : joint A in the inner / outer dead-center position
- B_i / B_a : joint B in the inner/outer dead-center position (dead-ends of transl. stroke)
- k_{A0} : circle on which A_0 is located, of center M_{A0}
- k_{Aa} : circle on which A_a is located, of center M_{Aa}
- φ_H: $\sphericalangle A_B A_0 A_i$, angle centered in A_0 and oriented from A_a to A_i, $\overline{\varphi}_H = \pi - \varphi_H$
- ψ: $\sphericalangle B_a B_0 B_i$, swinging angle centered in B_0 and oriented from B_a to B_i
- e: eccentricity



PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard



Synthesis 2: Dead center position synthesis

Geometric tools for synthesis

- Tools for design
- Synthesis
  - 3 position
  - Dead Center
  - Roberts-Cheb.
- Applications
- Conclusion

Constructing circle K_{A0}

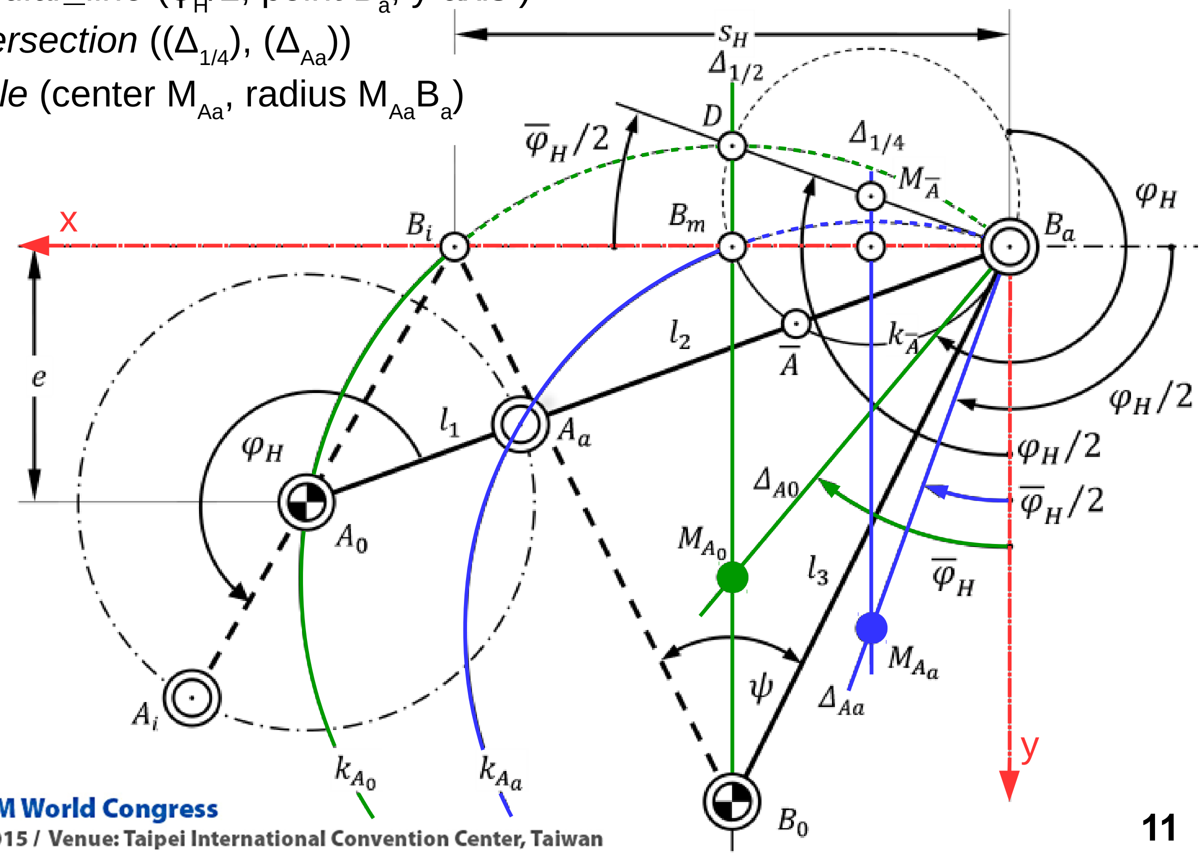
- line ($\Delta_{1/2}$) = *right_bisector* (B_i,B_a)
- line (Δ_{A0}) = *angular_line* (angle $\bar{\varphi}_H$, point B_a, y-axis)
- point M_{A0} = *intersection* (($\Delta_{1/2}$), (Δ_{A0}))
- circle k_{A0} = *circle* (center M_{A0}, radius $M_{A0}B_a$)

Constructing circle K_{Aa}

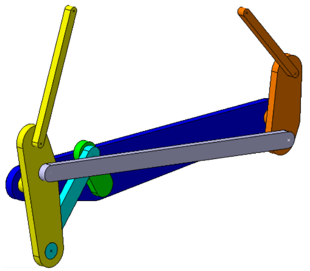
- line ($\Delta_{1/4}$) = *right_bisector* (B_m, B_a)
- line (Δ_{Aa}) = *angular_line* ($\bar{\varphi}_H$/2, point B_a, y-axis)
- point M_{Aa} = *intersection* (($\Delta_{1/4}$), (Δ_{Aa}))
- circle k_{Aa} = *circle* (center M_{Aa}, radius $M_{Aa}B_a$)

Constructing frame axes

- x-axis = half-line starting in B_a, directed by B_a B_i
- y-axis = *angular_line* (90°, point B_a, x-axis)



PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard



Synthesis 3: Roberts-Chebyshev substitution theorem

Geometric tools for synthesis

- Tools for design
- **Synthesis**
  - 3 position
  - Dead Center
  - Roberts-Cheb.
- Applications
- Conclusion

Notations

- A_0B_0BA the reference 4-bar mechanism
- **ABK: triangular coupler link**
- Angles κ = ∢BAK λ = ∢KBA
- Lengths k = AK l = BK

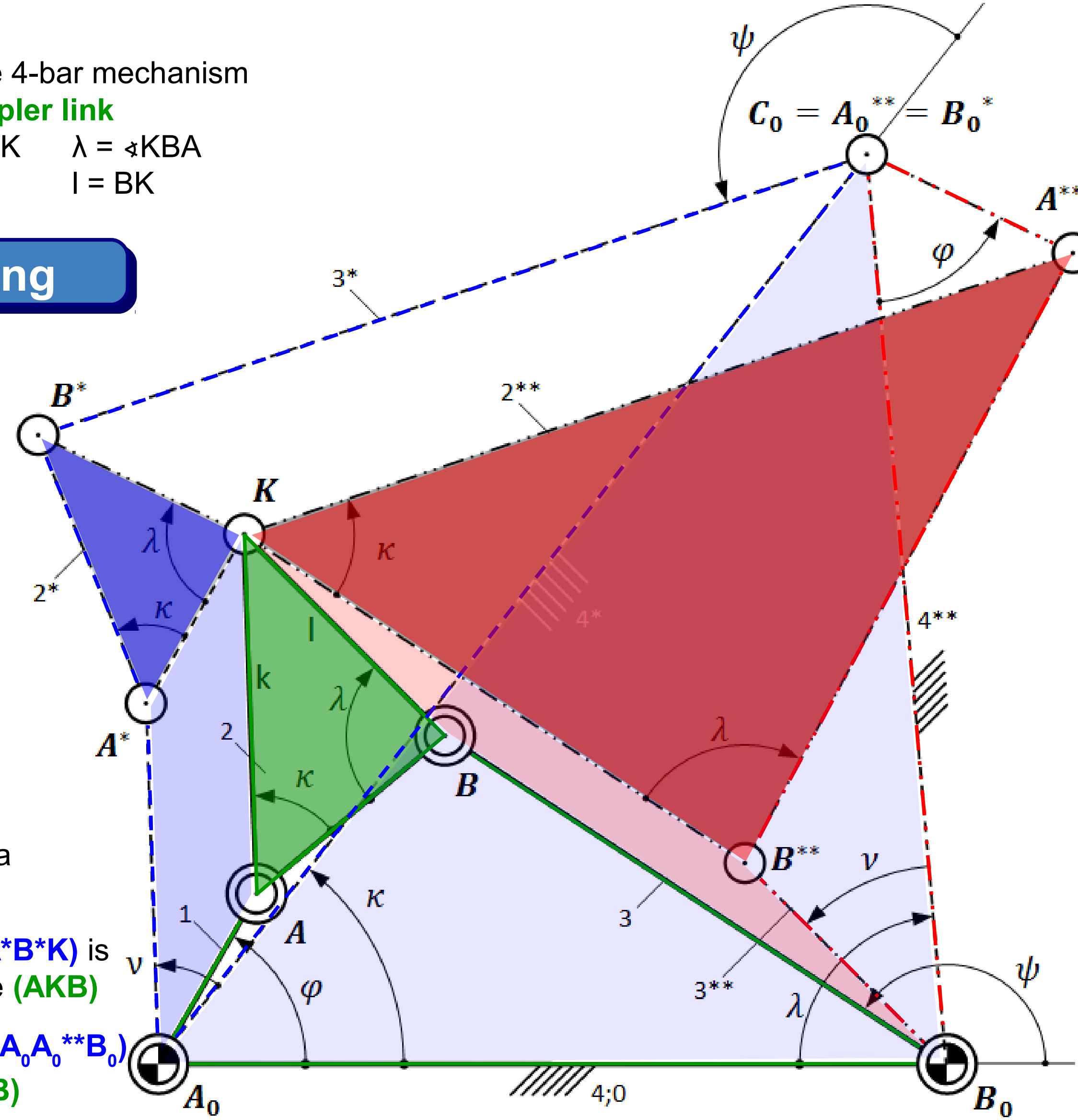
Problem setting

The ROBERTS-CHEBYSHEV-theorem can generate two 4-bar mechanisms with the same coupler curve of a coupler point K from A_0B_0BA

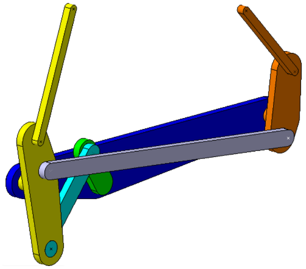
- $A_0B_0{}^*B^*A^*$
- $A_0{}^{**}B_0B^{**}A^{**}$

Algorithm

- A* so that A_0A^*KA is a *parallelogram*
- B* so that **triangle (A*B*K)** is *homothetic* to triangle **(AKB)**
- $A_0{}^{**}$ so that **triangle ($A_0A_0{}^{**}B_0$)** is *homothetic* to **(AKB)**

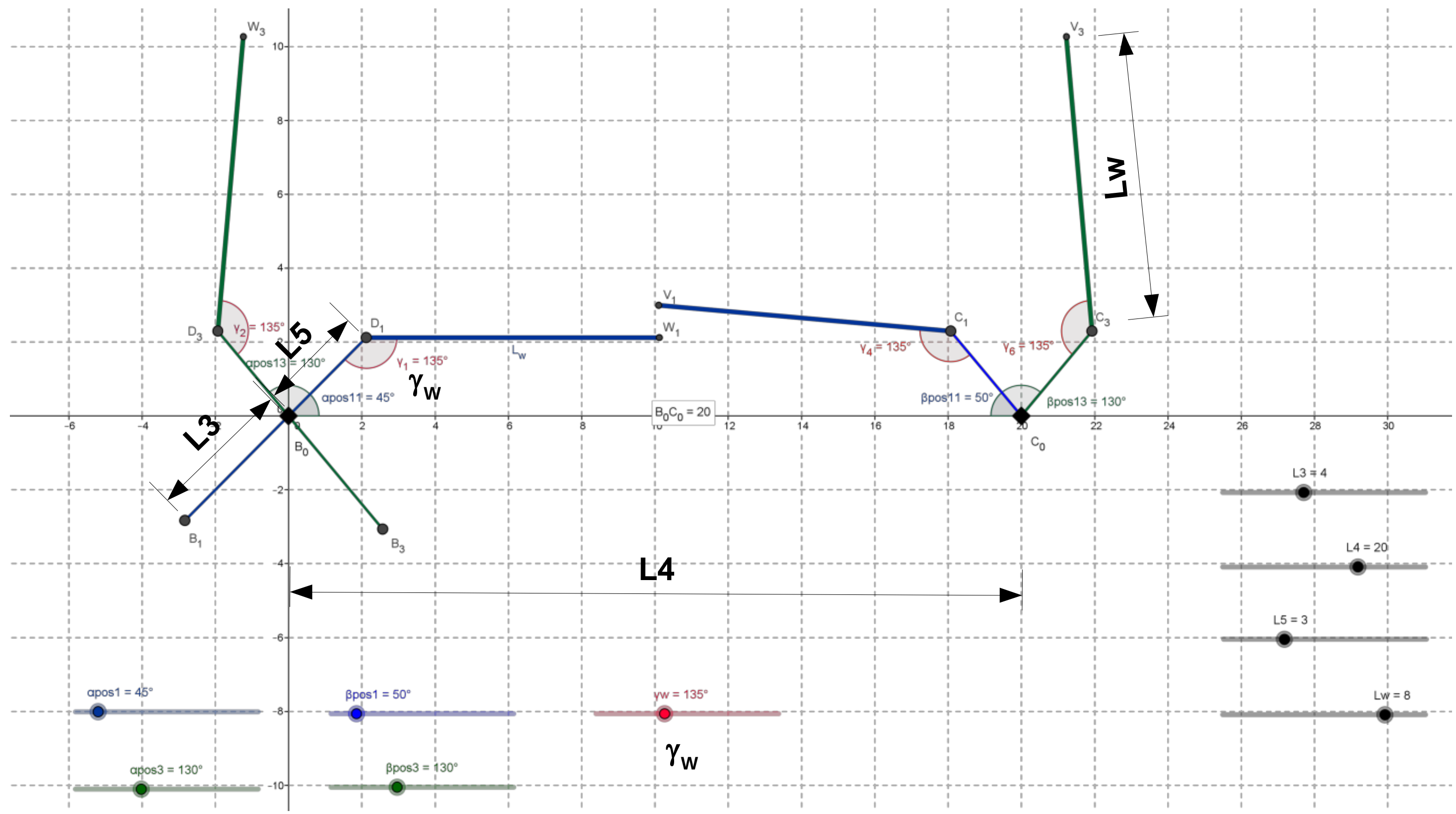


PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard



Application 1: Synthesis of a planar windscreen wiper mechanism with IGS

Problem specifications

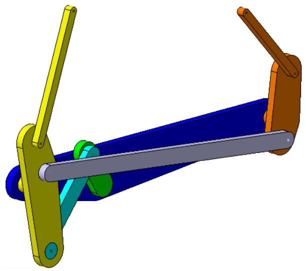


Left angular stroke

Right angular stroke

γ_w

PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard

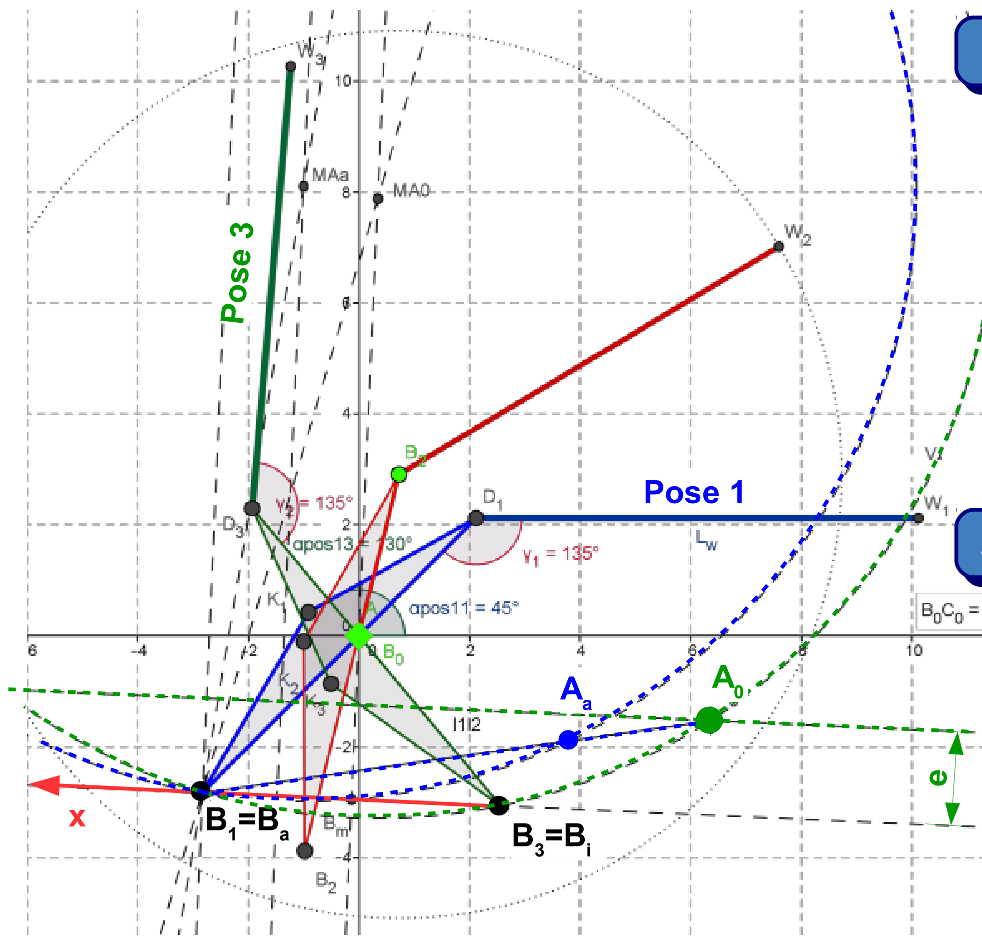


Application 1: Synthesis of a planar windscreen wiper mechanism with IGS

Geometric tools for synthesis

- Tools for design
- Synthesis
- Applications
  - Planar
  - Spherical
- Conclusion

Dead center position synthesis of the 4 bar mechanism for the actuation



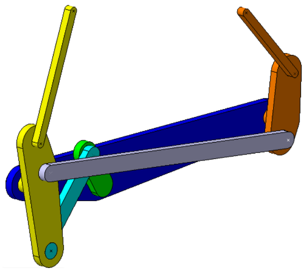
Problem setting

- Given the inner position 1 (α_1) & the outer position 3 (α_3) → swinging angle ψ
- Given the rocker length L_3
- Given the time ratio forward/backward
- Given the eccentricity e
- Find the actuated joint A_0
- Find the A_a joint (crank-coupler)

Solution

- Draw the stroke x axis
- Construct circle k_{A0}
- A_0= intersection (K_{a0}, parallel (x,e))
- Construct circle k_{Aa}
- A_a= *intersection* (k_{Aa}, [B_aA_0])

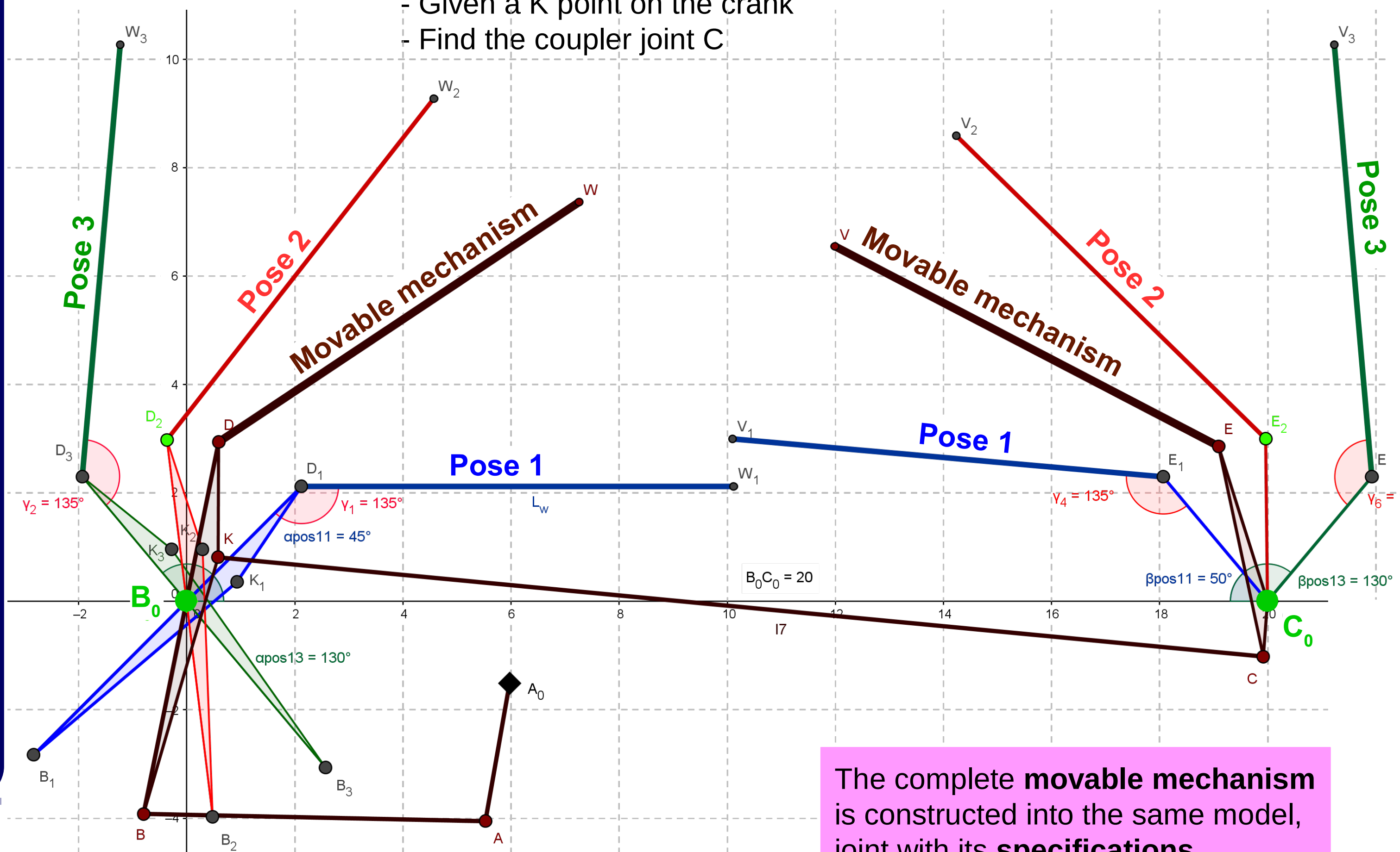
PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard



Application 1: Synthesis of a planar windscreen wiper mechanism with IGS

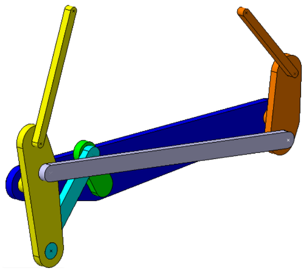
3 position synthesis of the 4-bar motion-replication mechanism

- Given the three poses of the wipers
- Given joints positions B_0 and C_0
- Given a K point on the crank
- Find the coupler joint C



The complete **movable mechanism** is constructed into the same model, joint with its **specifications**

PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard

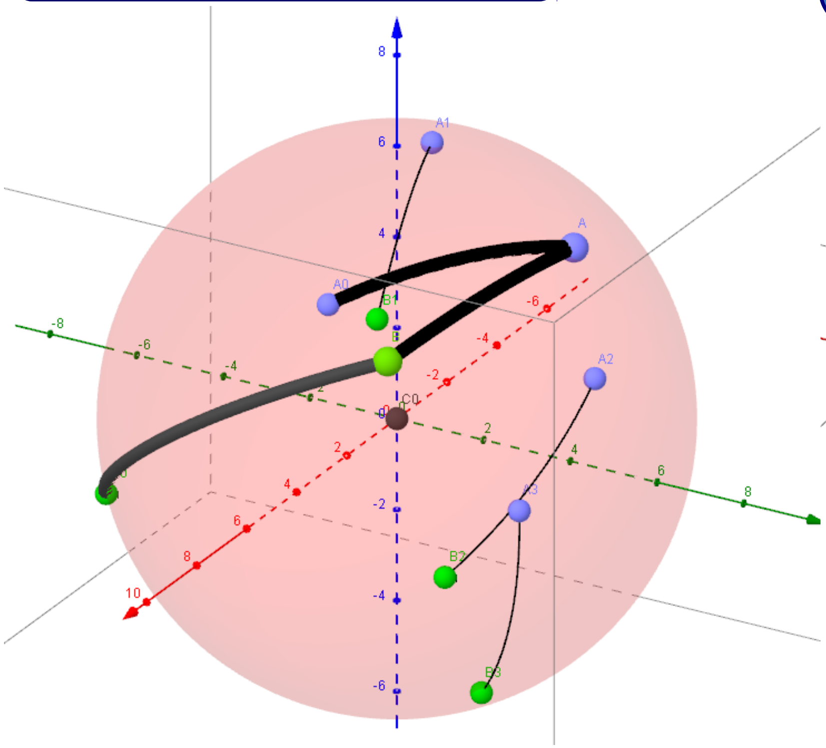


Application 2: Synthesis of spherical mechanisms

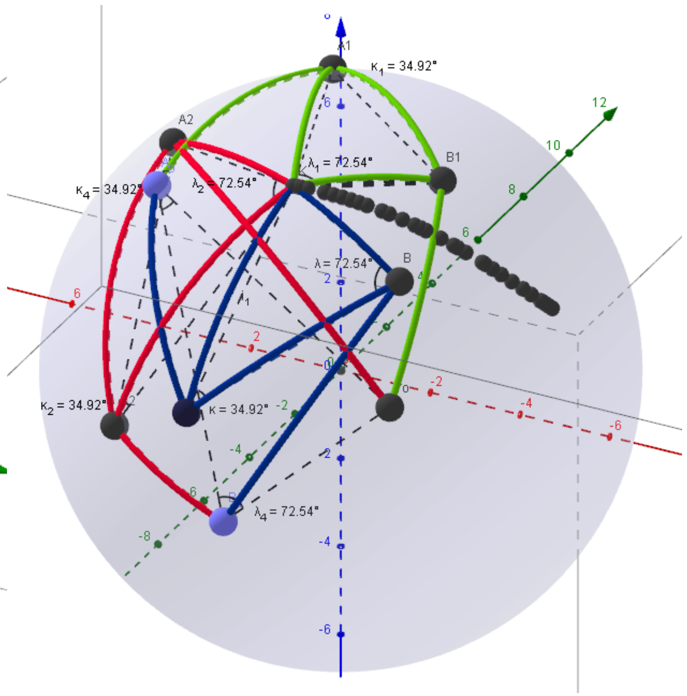
Geometric tools for synthesis

- Tools for design
- Synthesis
- Applications
  - Planar
  - Spherical
- Conclusion

3 position synthesis

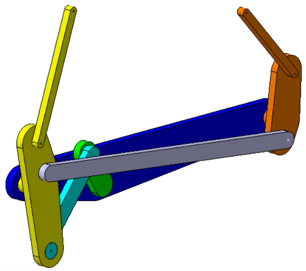


Roberts-Chebyshev substitution



- Extension to 3D spherical geometry is easy

PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard



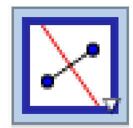
Dimensional synthesis with an IGS

Geometric tools for synthesis

- Tools for design
- Synthesis
- Applications
- Conclusion
  - IGS1 vs. IGS2
  - IGS vs. CAD
  - Conclusion

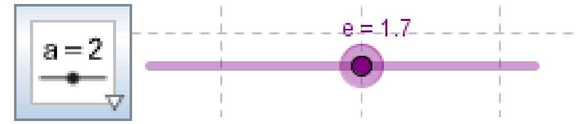
Geogebra vs. Cinderella

- Overall, both can do the job
- Geogebra has simpler ergonomics for
  - Parametrization
  - Angle transfer
  - Perpendicular bisector
- Other advantages of Geogebra
  - Free labeling of elements
  - Algebraic display (eq., coord.)
  - Fade out of construction elements
  - Pan-zoom



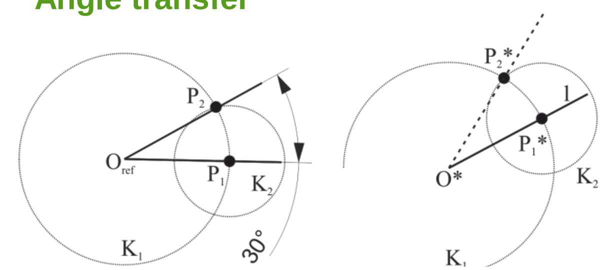
Parametrizing

Cinderella: variable = segment length (4 operations required)

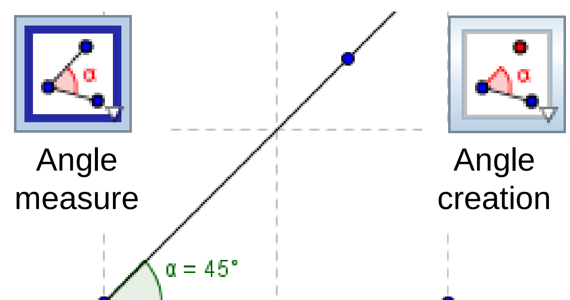


Geogebra: dedicated parameter tool

Angle transfer

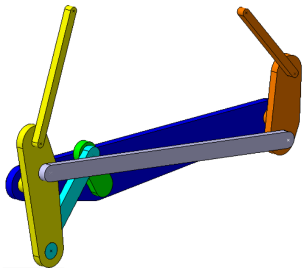


Cinderella: requires a construction



Geogebra: 2 dedicated tools

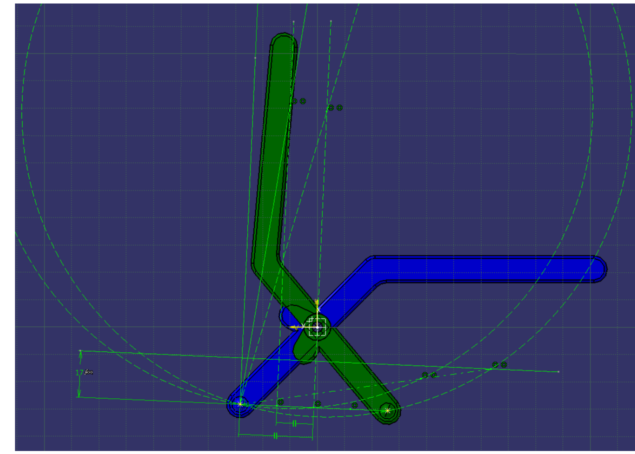
PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard

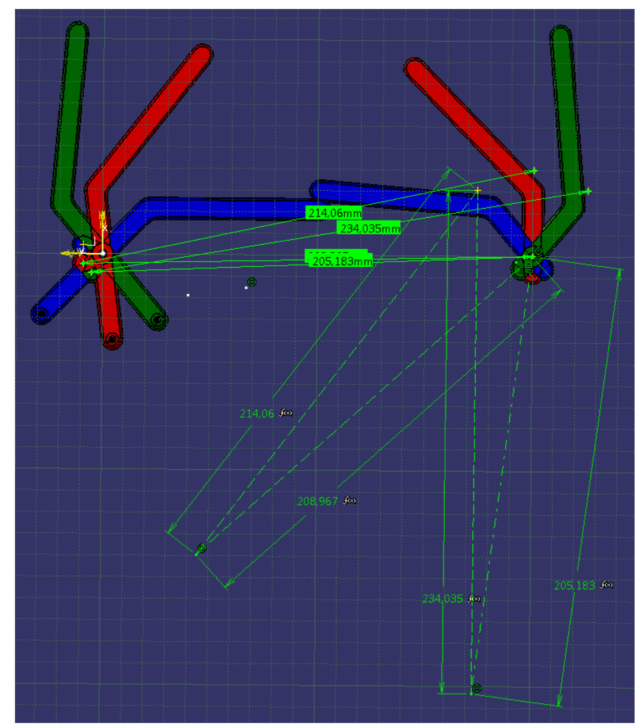


Dimensional synthesis with a CAD software

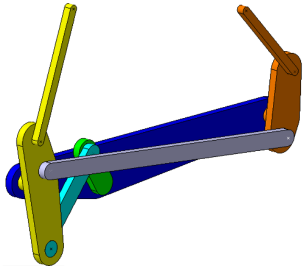
Catia vs. Inventor

- Application 1 was reproduced both with Catia V5 and Inventor
- **Procedure** with Catia V5
  - Define a skeleton part in assembly mode
  - 3 poses = 3 reference planes
  - Each construction requires a new part
  - Publication required for using length measures in other parts
  - The designer must:
    - anticipate synthesis **steps**
    - choose what will be **published**
    - choose the correct **inter-part references**
- Overall, Catia V5 is **less intuitive** than the IGSs and less tolerant with respect to mistakes
- Inventor has advantages over Catia V5 for synthesis:
  - Creation or points/lines/planes refs in assembly mode
  - Constraint « Has the same length as »
  - No time-consuming « publishing » concept





PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard



Conclusion

Geometric tools for synthesis

- Tools for design
- Synthesis
- Applications
- Conclusion
  - IGS₁ vs. IGS₂
  - IGS vs. CAD
  - Conclusion

Tool comparison

- Mechanism dimensional synthesis was performed with **several CAD and IGS tools**
- IGS tools prove to be **more time efficient** than CAD software
  - They help to concentrate on the skeleton only
- Geogebra **requires less operations** than Cinderella for the same task

	Parametrize	Transfer angles	Transfer lengths	Draw perpen-dicular bisectors	Find rotating point (position synthesis)
Cinderella©	4	8	1	7	2
GeoGebra©	1	1 (2)	1	3	2

Towards better tools for synthesis

- CAD software should **take inspiration** from IGS for dimensional synthesis
- Towards new CAD tools that integrate in the same model:
  - **Specifications**
  - A **mechanism skeleton** obtained by dimensional synthesis
  - A **3D model parametrized** by the skeleton

Demo

PRAUSE Isabel
FAUROUX Jean-Christophe
HÜSING Mathias
CORVES Burkhard