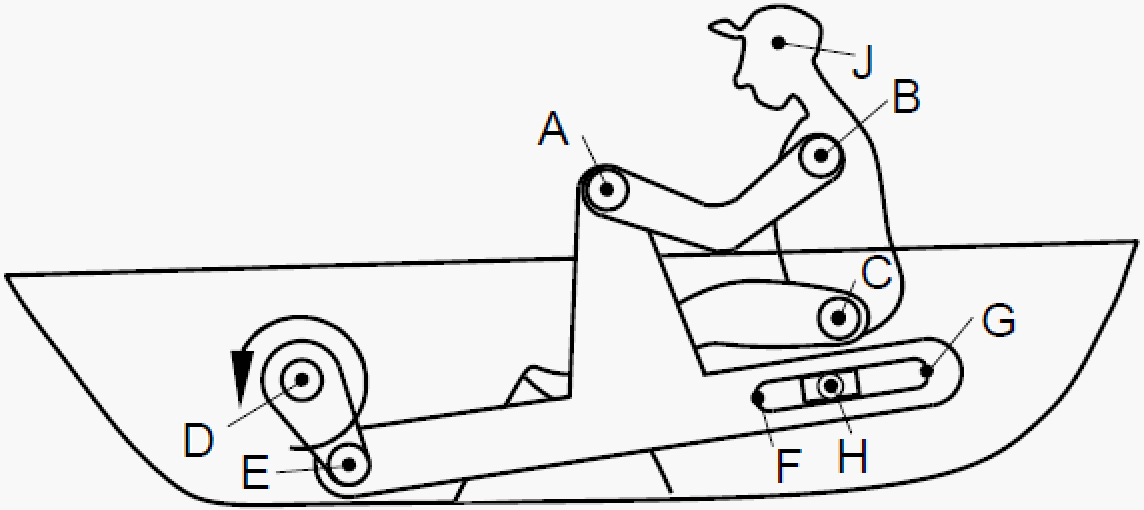
Dynamics of Mechanical Systems

2023/24

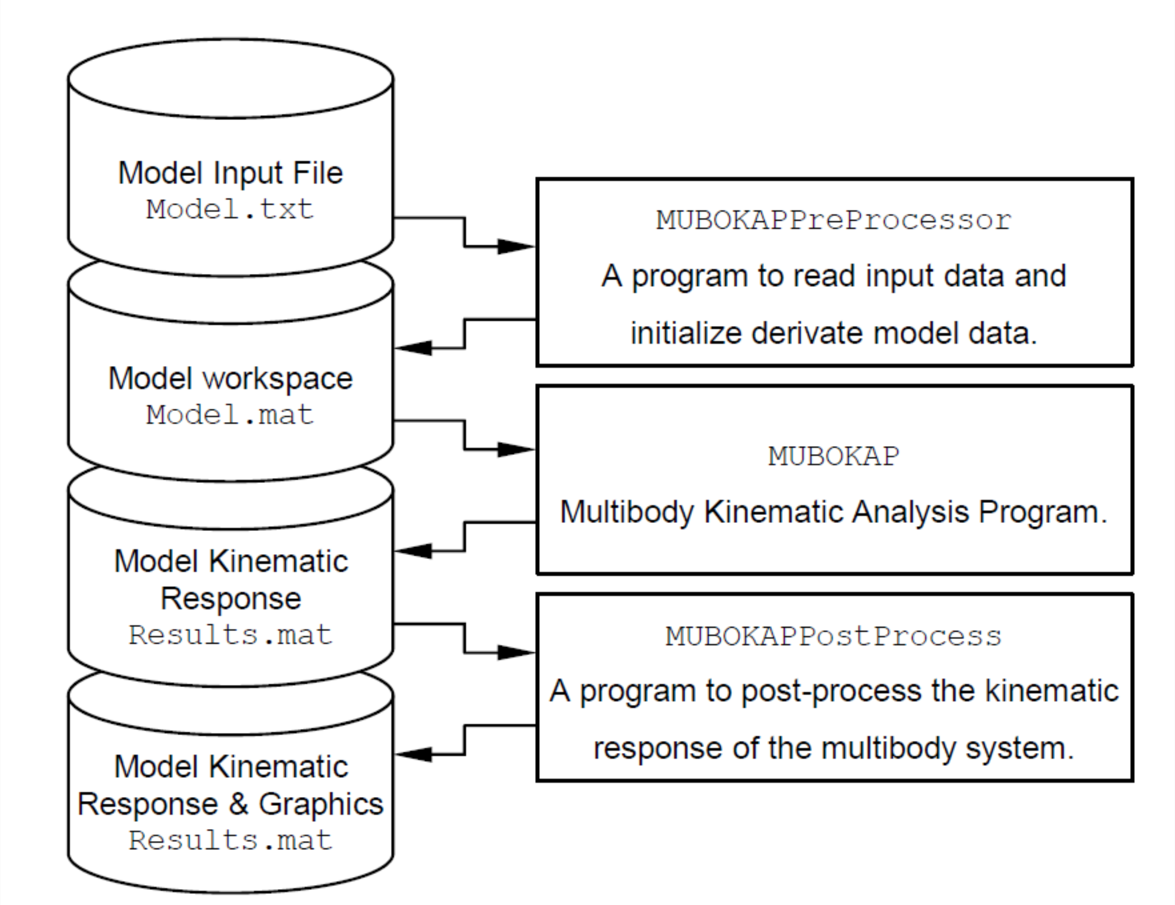
Summary

Kinematic analysis of mechanical systems using Cartesian Coordinates.

Application to the toy rower using MuboKAP.



Dynamics of Mechanical Systems



The kinematic analysis program MUBOKAP has the same structure and methodological implementation as the first kinematic analysis program used before.

Dynamics of Mechanical Systems

Input structure and Pre-Processor

The modeling data and analysis profile is supplied to MuboKAP pre-processor via an ASCII text file (with the extension '.txt'). This input file is organized with the following structure:

Model dimensions (1st line): Information on the dimensions of the multibody system (data separated by space, tab, or comma), which includes, by order:

- NBody – Number of rigid bodies in the model
- NRevolute – Number of revolute joints
- NTranslation – Number of translation joints
- NRevRev – Number of composite revolute-revolute joints
- NTraRev – Number of composite revolute-translation joints
- NRigid – Number of rigid joints
- Dummy – Entry reserved for future developments (enter '0')
- NSimple – Number of simple joints
- NDriver – Number of driving constraints
- NPointsOfInt – Number of points of interest for reporting

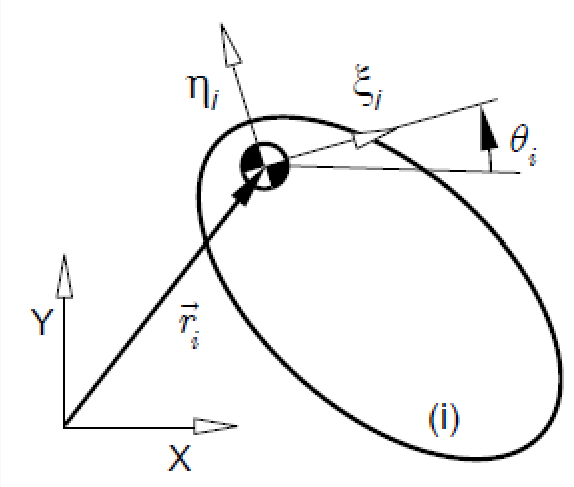
Dynamics of Mechanical Systems

<u>Input structure and Pre-Processor</u>

The next set of information consists in the rigid bodies estimated positions and orientations (for the definition of the initial position vector to be provided to Newton-Raphson). The input file must have one line for each rigid body with the following information:

Rigid bodies data (From lines 2 to NBody + 2): Information on the position and orientation of each of the rigid bodies of the model, which is constituted by:

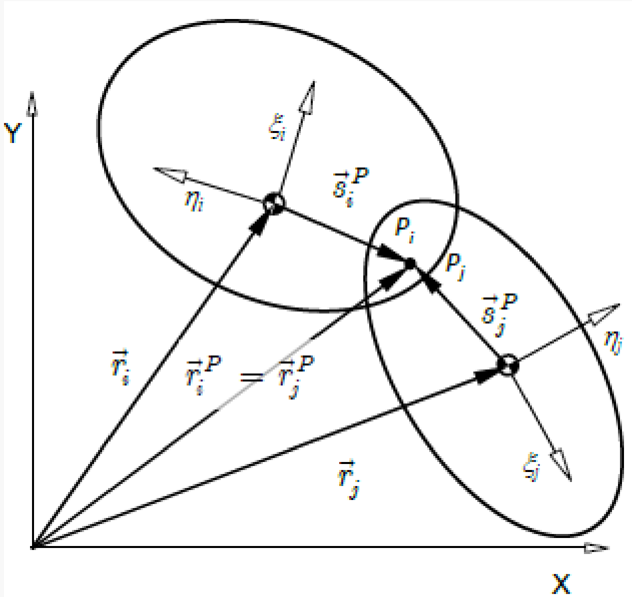
- x_i – Position along X in the body fixed coordinate system
- y_i – Position along Y in the body fixed coordinate system
- θ_i – Angular orientation of the rigid body (in radians)



Input structure and Pre-Processor

The next set of data concerns the information regarding the revolute joints. The required modelling data to be provided includes:

$$\mathbf{\Phi}^{(Rev,2)} = \mathbf{r}_i + \mathbf{A}_i \mathbf{s}_i'^{P} - \mathbf{r}_j - \mathbf{A}_j \mathbf{s}_j'^{P}$$



Revolute joints data (From lines Nbody + 3 to NBody + NRevolute + 3): Information on the rigid bodies of the model connected by the joint and location of the required geometric features:

- i – Number of the 1st body connected by the revolute joint
- j – Number of the 2nd body connected by the revolute joint
- ξ_i^P – ξ coordinate of point P in body i
- η_i^P – η coordinate of point P in body i
- ξ_j^P – ξ coordinate of point P in body j
- η_j^P – η coordinate of point P in body j

Input structure and Pre-Processor

NBody NRevolute NTranslation NRevRev NTraRev Nrigid 0 Nsimple NDriver NPointsOfInt

…

After the description of all parameters from the 1st line, the last two lines address data regarding numerical methods and the time profile, respectively.

Numerical methods data (Line …): Information on numerical methods tolerances, which includes

- MaxIter – Maximum number of iterations for the nonlinear solvers
- Tolerance – Numerical tolerance for the solution of nonlinear equations

Time analysis profile data (Line …): Information on time period for the analysis and the reporting time step:

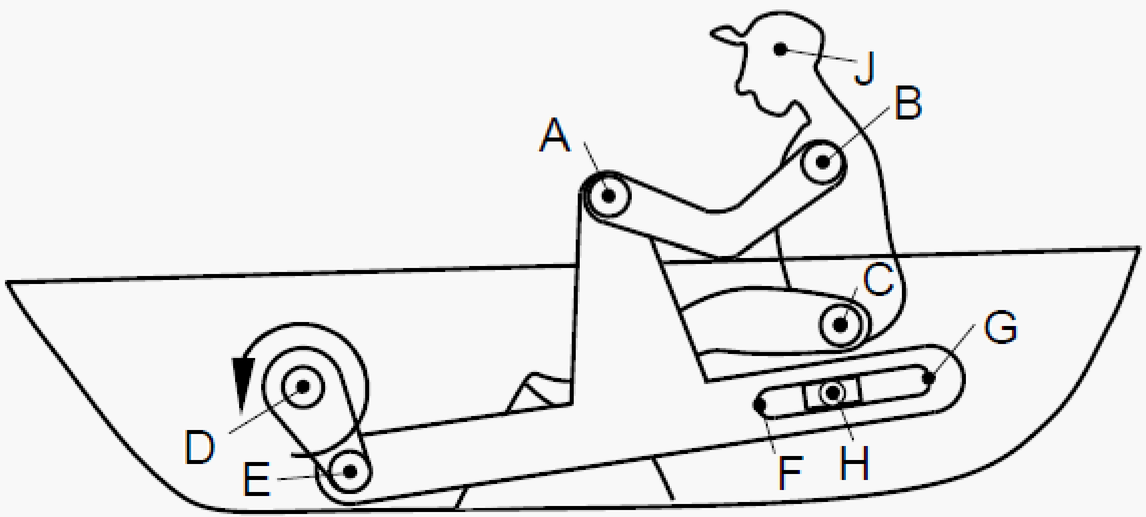
- TStart – Starting time for the kinematic analysis
- TStep – Time step for both analysis and reporting
- TEnd – Final time for the kinematic analysis

In the pre-processing stage, all data are assumed to be consistent, and all constraints are independent.

Dynamics of Mechanical Systems

Application case: Toy rower

The toy rower is a mechanical system in which the crank link DE, pinned to the body of the boat, is rotated with a constant angular velocity. The coupler link EAFG, to which the rower has the hands pinned, slides along a body pinned to the boat at point H. The rower, whose upper body is pinned to the boat at point C, has a rocking motion as it rotates about point C, while the arm is pinned to the coupler link at point A. The general dimensions of the mechanical system, shown in the figure, are obtained by a direct measurement of the figure and constant scaling.



$$l_{AB} = 1.30$$

$$l_{BC} = 0.97$$

$$l_{EF} = 2.48$$

$$l_{FG} = 1.02$$

$$l_{CH} = 0.50$$

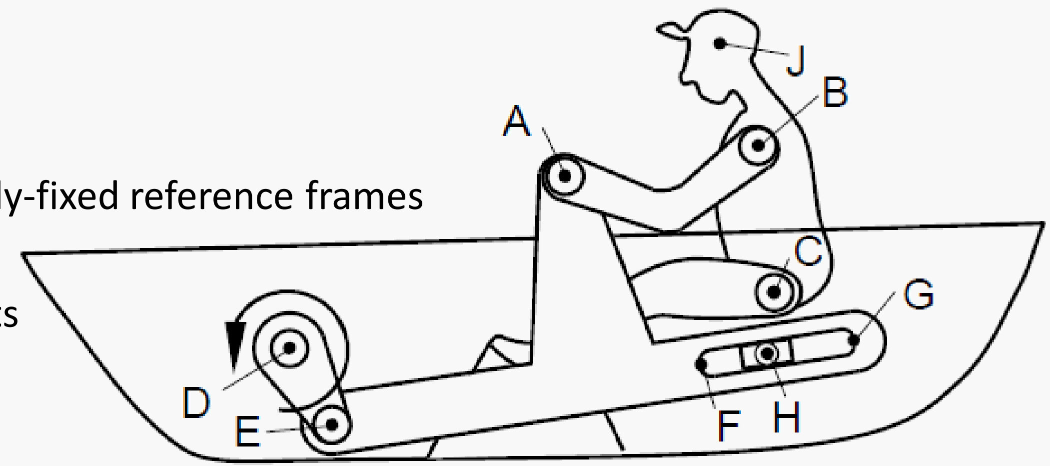
MuboKAP Application Case

Application case: Toy rower

The toy rower is a mechanical system in which the crank link DE, pinned to the body of the boat, is rotated with a constant angular velocity. The coupler link EAFG, to which the rower has the hands pinned, slides along a body pinned to the boat at point H. The rower, whose upper body is pinned to the boat at point C, has a rocking motion as it rotates about point C, while the arm is pinned to the coupler link at point A. The general dimensions of the mechanical system, shown in the figure, are obtained by a direct measurement of the figure and constant scaling.

Mechanical system analysis

- Analyze mechanism
- Define rigid bodies and body-fixed reference frames
- Define system coordinates
- Define kinematic constraints
- Define driver constraints
- Define initial condition
- Define kinematic analysis parameters



Dynamics of Mechanical Systems

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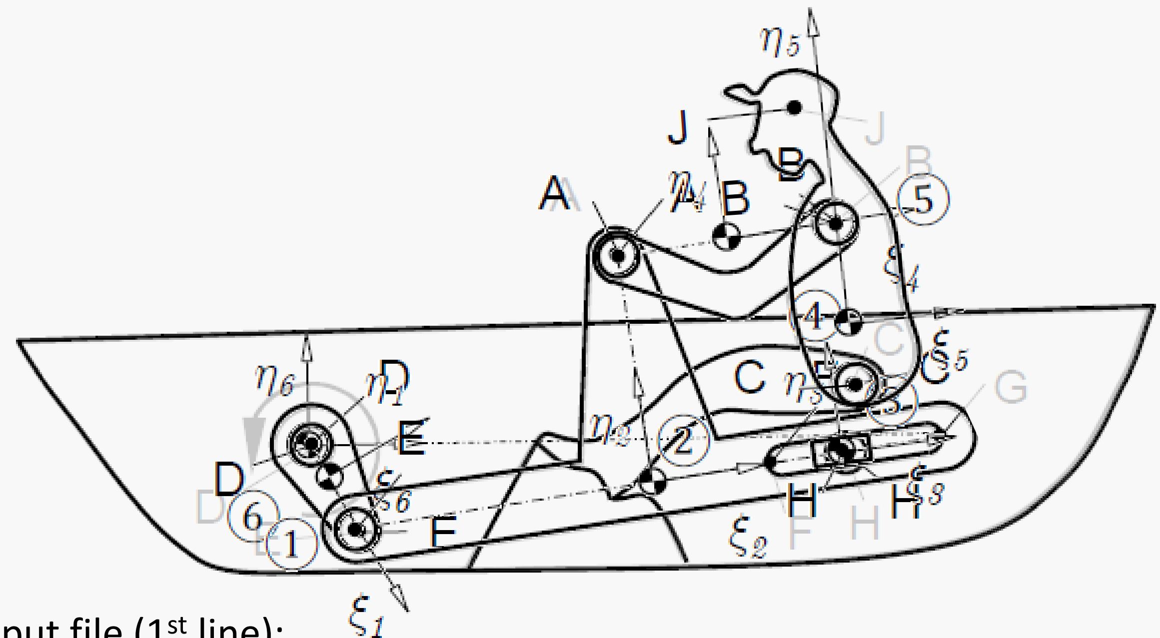

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Input file (1st line):

NBody NRevolute NTranslation NRevRev NTraRev Nrigid 0 Nsimple NDriver NPointsOfInt

Dynamics of Mechanical Systems

MuboKAP Application Case

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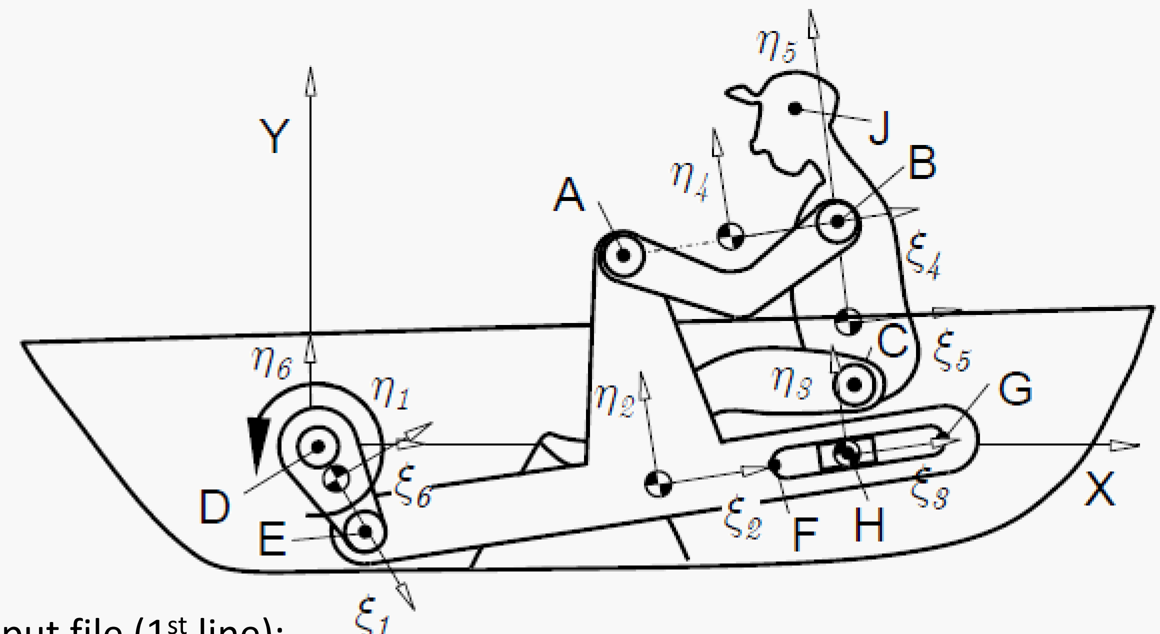

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6 NRevolute NTranslation NRevRev NTraRev Nrigid 0 Nsimple NDriver NPointsOfInt

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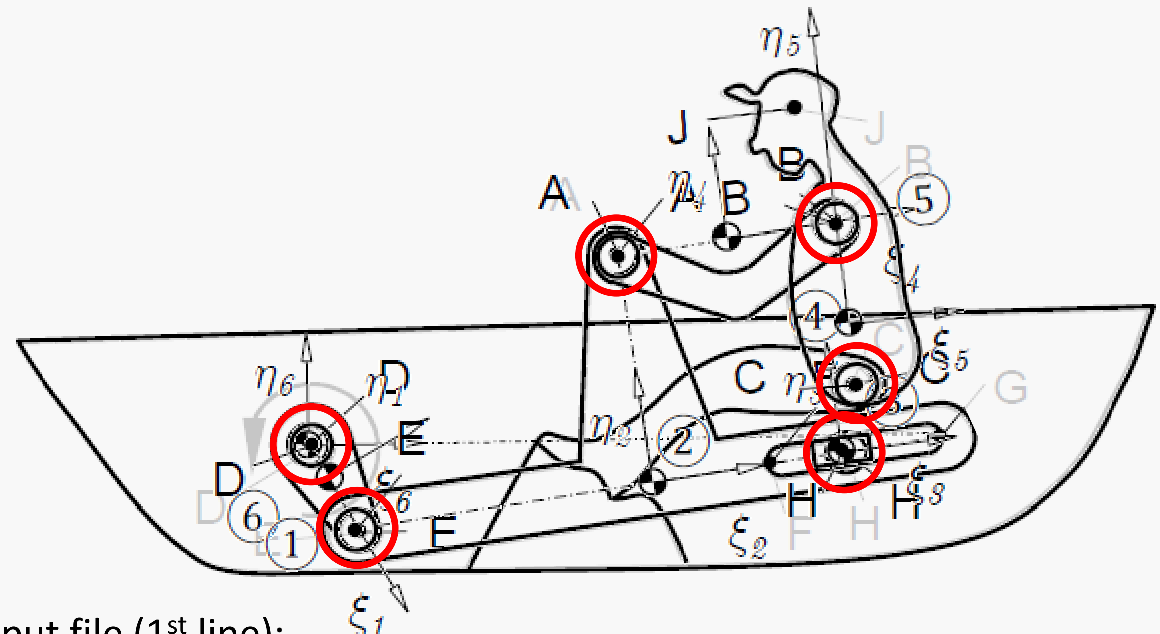

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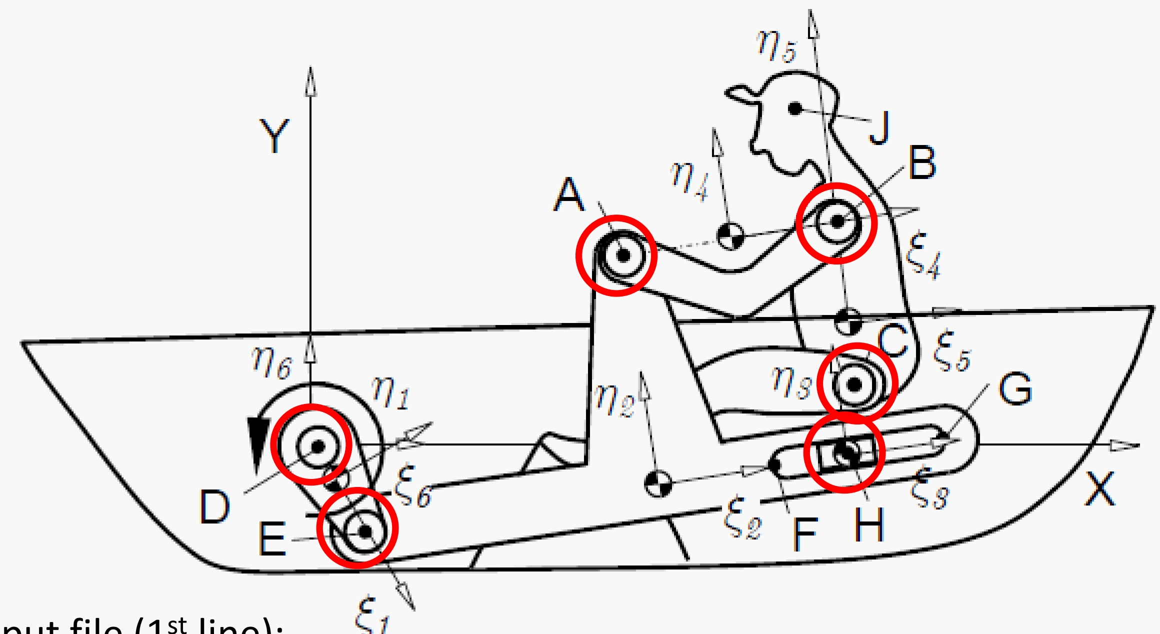

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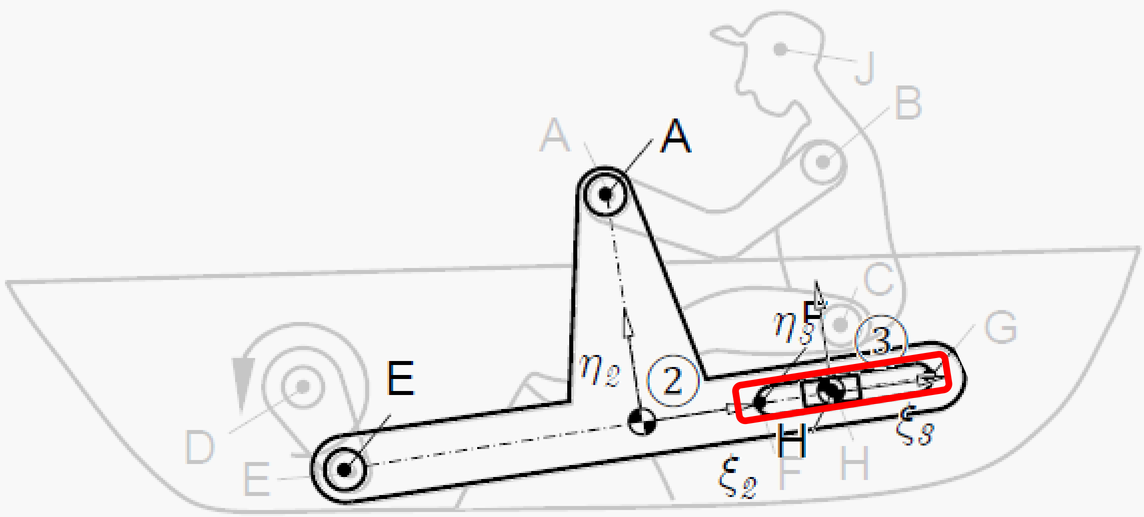

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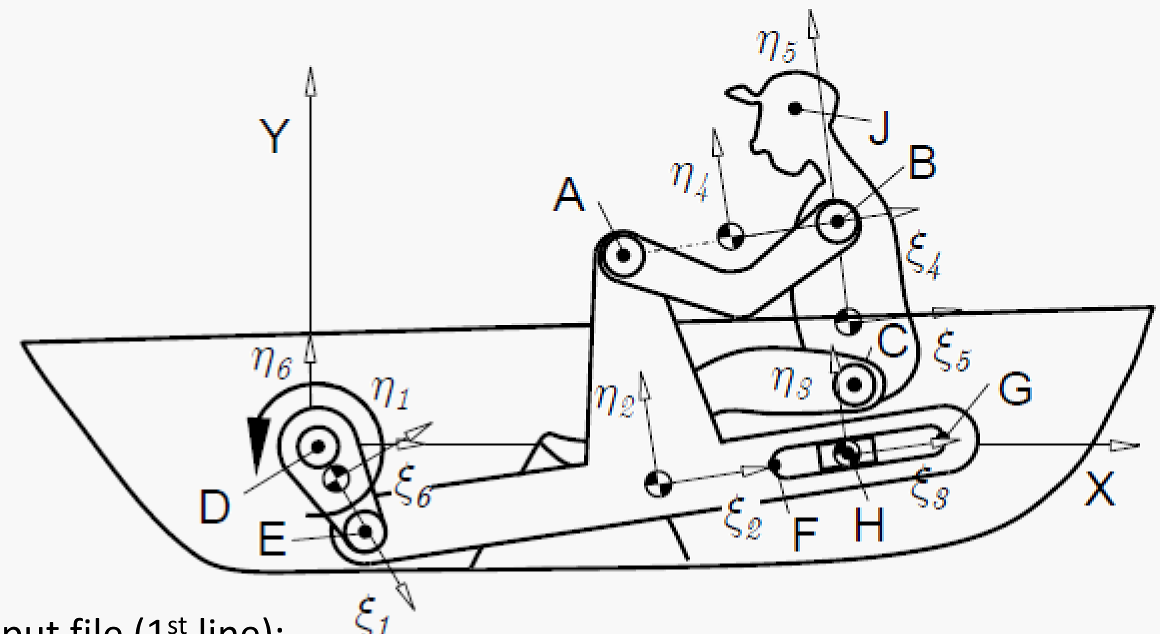

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Input file (1^{st} line):

6 6 1 NRevRev NTraRev Nrigid 0 Nsimple NDriver NPointsOfInt

Dynamics of Mechanical Systems

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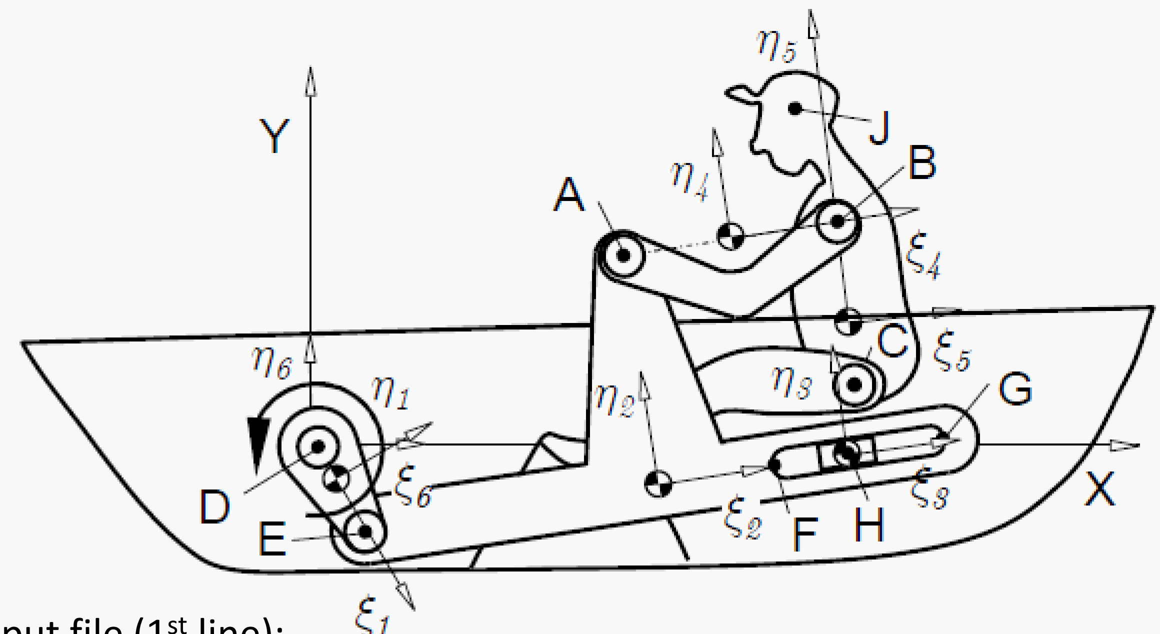

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$l_{FG} = 1.02$

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Input file (1st line):

6 6 1 0 0 0 0 3 NDriver NPointsOfInt

$$n_{dof} = 6 \times 3 - (6 \times 2 + 2 + 3) = 1$$

Dynamics of Mechanical Systems

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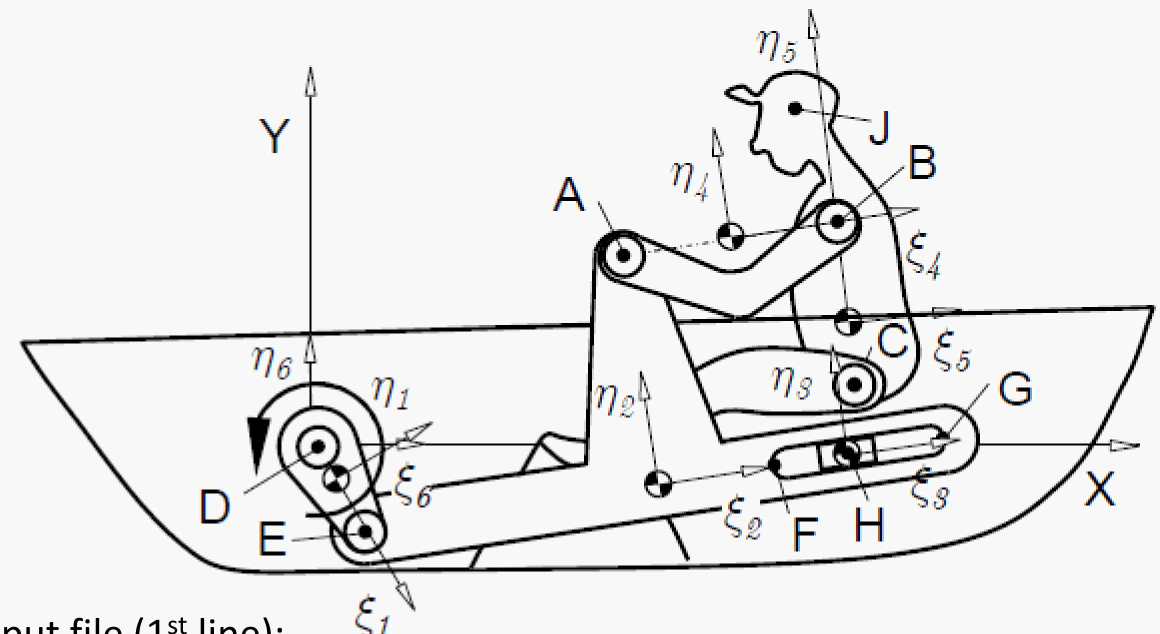

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Input file (1st line):

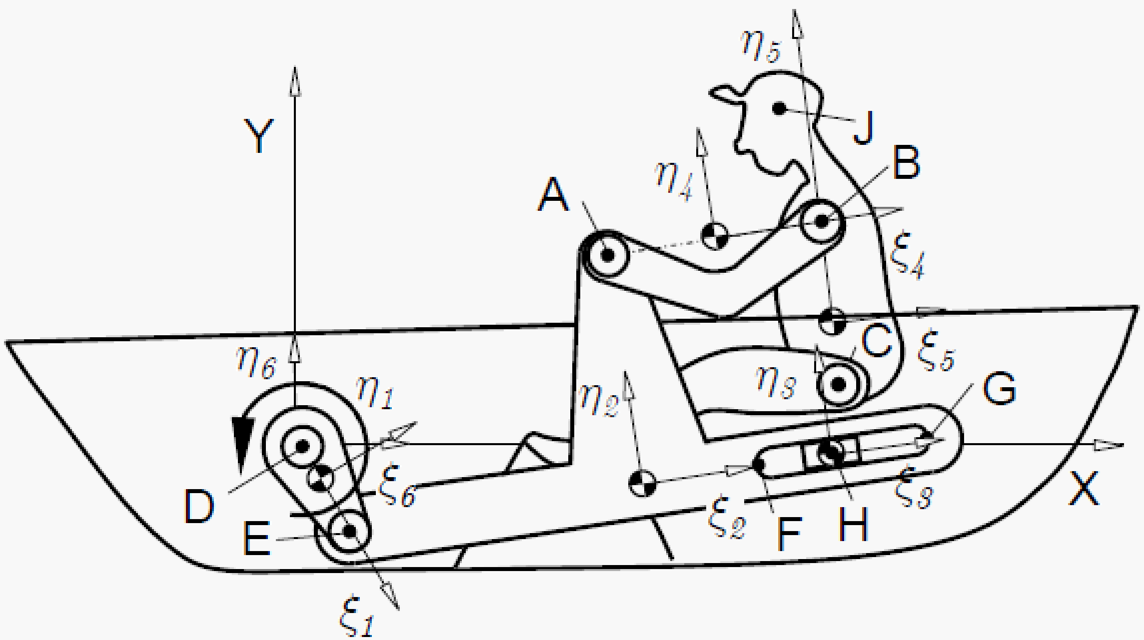
6 6 1 0 0 0 0 3 1 NPointsOfInt

Application case: Toy rower

After the model dimensions, the initial position and orientation of each rigid body, required to start the kinematic analysis, need to be provided. They are estimated from the figure:

$$\mathbf{r}_1 = \begin{Bmatrix} 0.15 \\ -0.20 \end{Bmatrix} \quad \mathbf{r}_2 = \begin{Bmatrix} 2.05 \\ -0.23 \end{Bmatrix} \quad \mathbf{r}_3 = \begin{Bmatrix} 3.18 \\ -0.13 \end{Bmatrix} \quad \mathbf{r}_4 = \begin{Bmatrix} 2.49 \\ 1.24 \end{Bmatrix} \quad \mathbf{r}_5 = \begin{Bmatrix} 3.20 \\ 0.74 \end{Bmatrix} \quad \mathbf{r}_6 = \begin{Bmatrix} 0.00 \\ 0.00 \end{Bmatrix}$$

$$\theta_1 = 300° \quad \theta_2 = 10° \quad \theta_3 = 10° \quad \theta_4 = 10° \quad \theta_5 = 10° \quad \theta_6 = 0°$$



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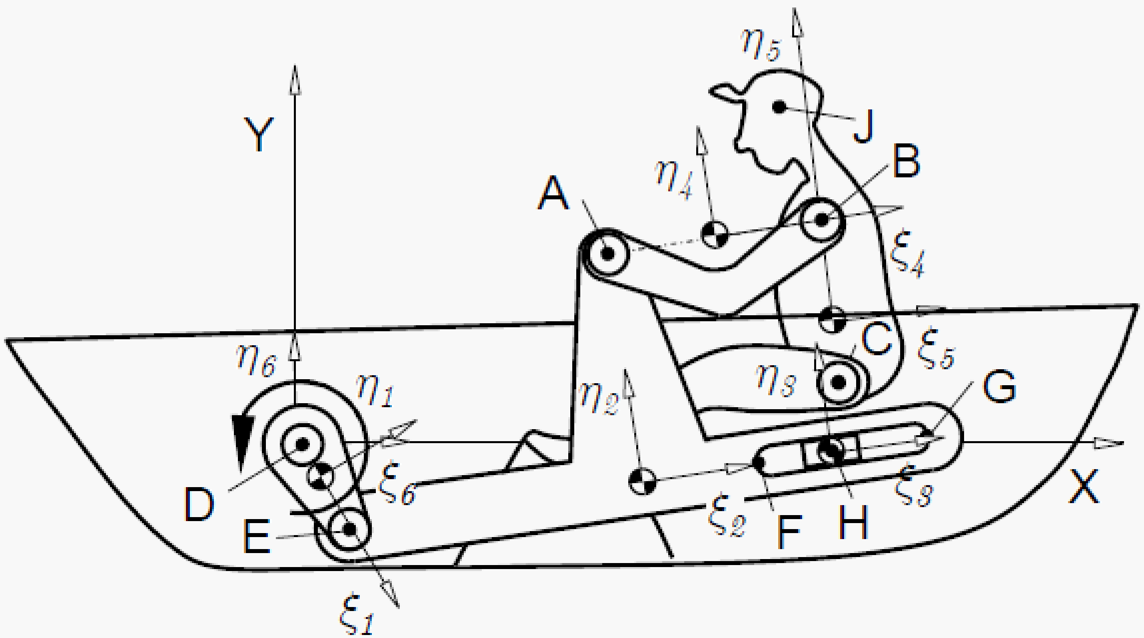
$$\theta_1 = 300^\circ \quad \theta_2 = 10^\circ \quad \theta_3 = 10^\circ \quad \theta_4 = 10^\circ \quad \theta_5 = 10^\circ \quad \theta_6 = 0^\circ$$

Input file:

```
6 6 1 0 0 0 0 3 1 2
0.150 -0.200 5.236
2.050 -0.230 0.174
3.180 -0.130 0.174
2.490  1.240 0.174
3.200  0.740 0.174
0.000  0.000 0.000
```



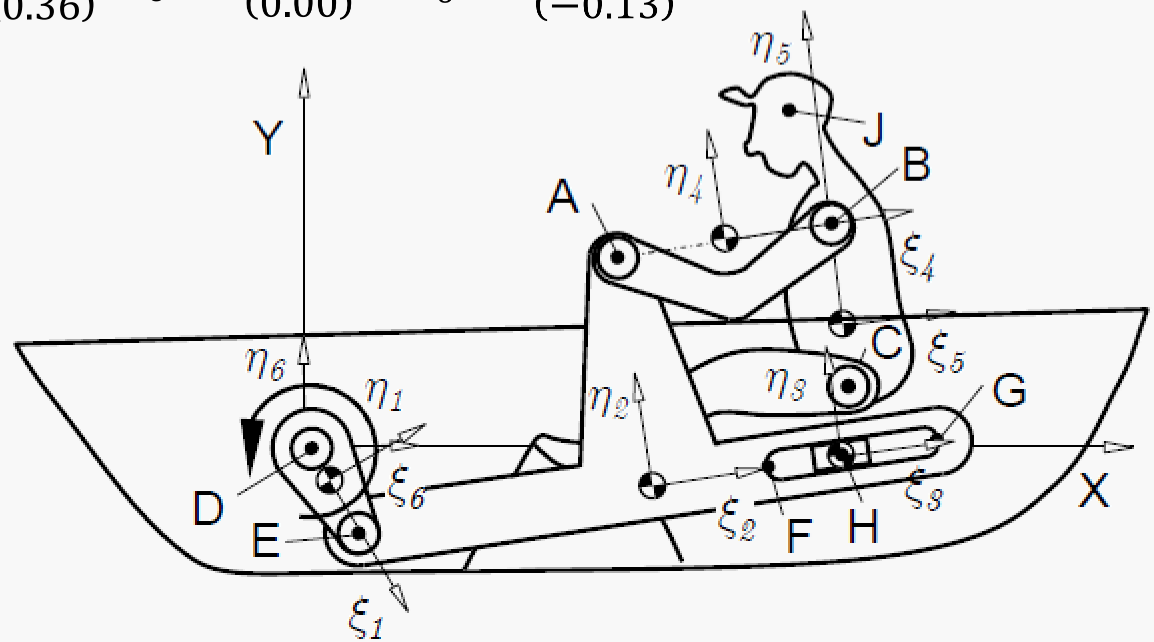
Application case: Toy rower

After the model dimensions, the initial position and orientation of each rigid body, required to start the kinematic analysis, need to be provided. They are estimated from the figure:

$$\mathbf{s}_1'^{D} = \begin{Bmatrix} -0.22 \\ 0.00 \end{Bmatrix} \quad \mathbf{s}_1'^{E} = \begin{Bmatrix} 0.36 \\ 0.00 \end{Bmatrix} \quad \mathbf{s}_2'^{A} = \begin{Bmatrix} 0.00 \\ 1.35 \end{Bmatrix} \quad \mathbf{s}_2'^{E} = \begin{Bmatrix} -1.78 \\ 0.00 \end{Bmatrix} \quad \mathbf{s}_2'^{F} = \begin{Bmatrix} 0.70 \\ 0.00 \end{Bmatrix} \quad \mathbf{s}_2'^{G} = \begin{Bmatrix} 1.72 \\ 0.00 \end{Bmatrix}$$

$$\mathbf{s}_3'^{H} = \begin{Bmatrix} 0.00 \\ 0.00 \end{Bmatrix} \quad \mathbf{s}_3'^{\hat{H}} = \begin{Bmatrix} 1.00 \\ 0.00 \end{Bmatrix} \quad \mathbf{s}_4'^{A} = \begin{Bmatrix} -0.65 \\ 0.00 \end{Bmatrix} \quad \mathbf{s}_4'^{B} = \begin{Bmatrix} 0.65 \\ 0.00 \end{Bmatrix} \quad \mathbf{s}_5'^{B} = \begin{Bmatrix} 0.00 \\ 0.60 \end{Bmatrix} \quad \mathbf{s}_5'^{C} = \begin{Bmatrix} 0.00 \\ -0.37 \end{Bmatrix}$$

$$\mathbf{s}_5'^{J} = \begin{Bmatrix} -0.15 \\ 1.32 \end{Bmatrix} \quad \mathbf{s}_6'^{C} = \begin{Bmatrix} 3.25 \\ 0.36 \end{Bmatrix} \quad \mathbf{s}_6'^{D} = \begin{Bmatrix} 0.00 \\ 0.00 \end{Bmatrix} \quad \mathbf{s}_6'^{H} = \begin{Bmatrix} 3.21 \\ -0.13 \end{Bmatrix}$$



Dynamics of Mechanical Systems

Application case: Toy rower

Input file:

```
6 6 1 0 0 0 0 3 1 2
0.150 -0.200 5.236
2.050 -0.230 0.174
3.180 -0.130 0.174
2.490  1.240 0.174
3.200  0.740 0.174
0.000  0.000 0.000
…
```

```
1 2  0.360  0.000 -1.780  0.000
2 4  0.000  1.350 -0.650  0.000
4 5  0.650  0.000  0.000  0.600
5 6  0.000 -0.370  3.250  0.360
3 6  0.000  0.000  3.210 -0.130
1 6 -0.220  0.000  0.000  0.000
2 3  0.700  0.000  1.720  0.000  0.000  0.000  1.000  0.000
6 1  0.000
6 2  0.000
6 3  0.000
…
```

Revolute

Ground

Translation

NBody	NRevolute	NTranslation	NRevRev	NTraRev	Nrigid	0	Nsimple	NDriver	NPointsOfInt
6	6	1	0	0	0	0	3	1	2

Dynamics of Mechanical Systems

Application case: Toy rower

Input file:

6 6 1 0 0 0 0 3 1 2
0.150 -0.200 5.236
2.050 -0.230 0.174
3.180 -0.130 0.174
2.490 1.240 0.174
3.200 0.740 0.174
0.000 0.000 0.000
…

Revolute:

1 2 0.360 0.000 -1.780 0.000
2 4 0.000 1.350 -0.650 0.000
4 5 0.650 0.000 0.000 0.600
5 6 0.000 -0.370 3.250 0.360
3 6 0.000 0.000 3.210 -0.130
1 6 -0.220 0.000 0.000 0.000

Translation:

2 3 0.700 0.000 1.720 0.000 0.000 0.000 1.000 0.000

Ground:

6 1 0.000
6 2 0.000
6 3 0.000

1 1 3 0 5.236 -6.2832 0.000 0.000

$$\mathbf{\Phi}^{(d,1)} = \theta_1 - (5.24 - 6.28 \times t)$$

Points of Interest:

2 0.000 1.350
5 -0.150 1.320

12 0.0000001
0.000 0.010 2.000

NBody	NRevolute	NTranslation	NRevRev	NTraRev	Nrigid	0	Nsimple	NDriver	NPointsOfInt
6	6	1	0	0	0	0	3	1	2

Dynamics of Mechanical Systems

MuboKAP Application Case

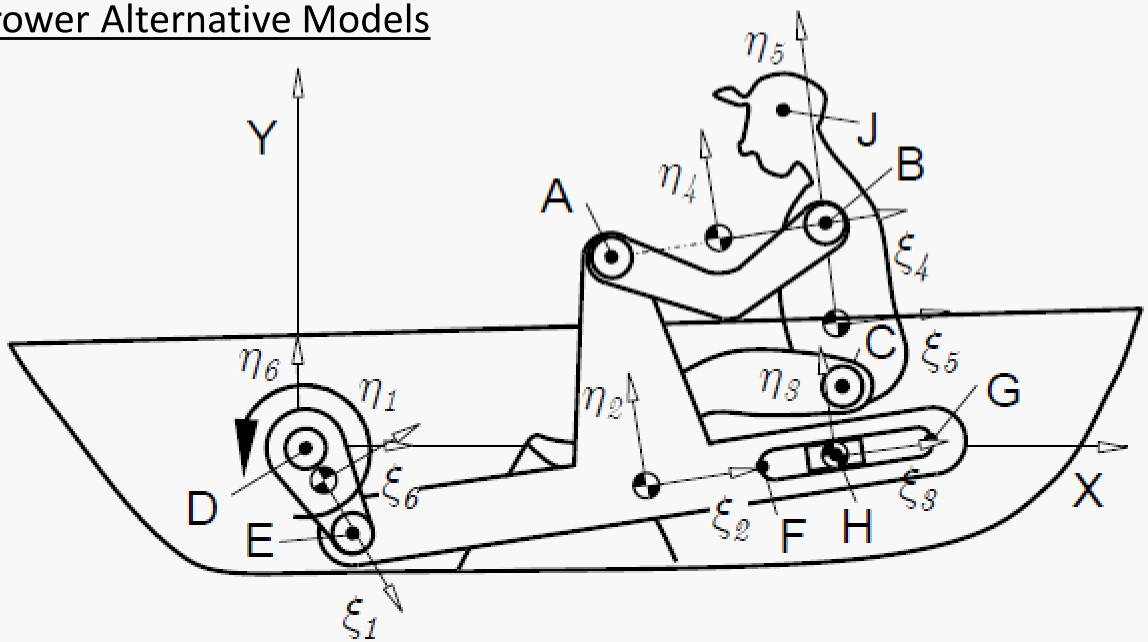
Application case: Toy rower Alternative Models

Nbody – 6

NRevolute – 6

NTranslation – 1

NSimple - 3



MuboKAP Application Case

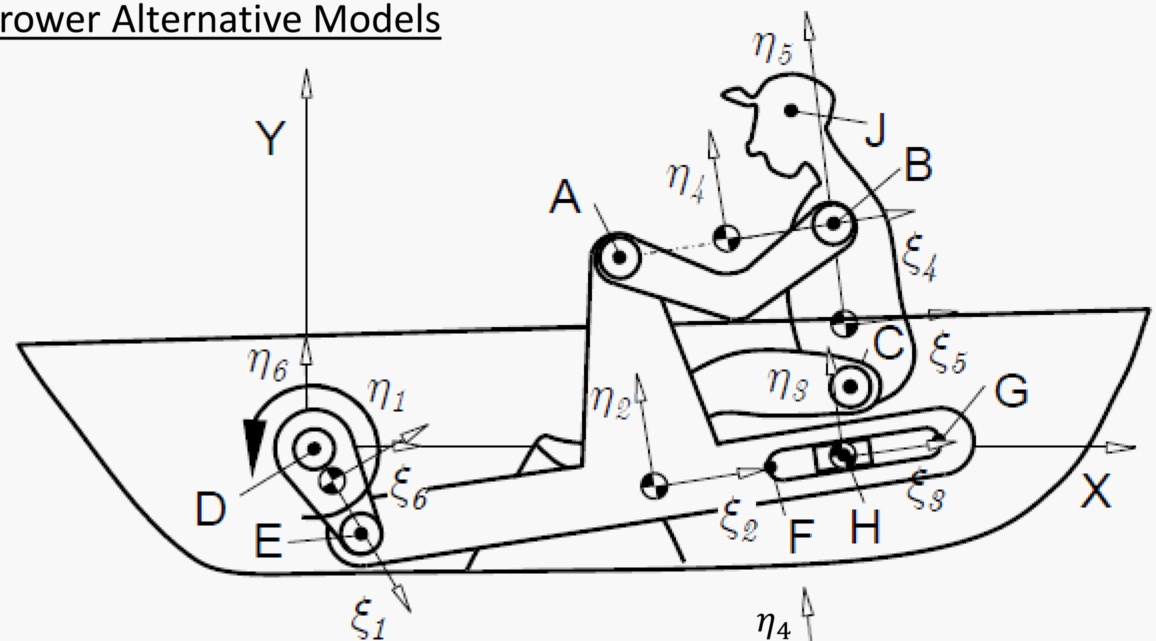
Application case: Toy rower Alternative Models

Nbody – 6

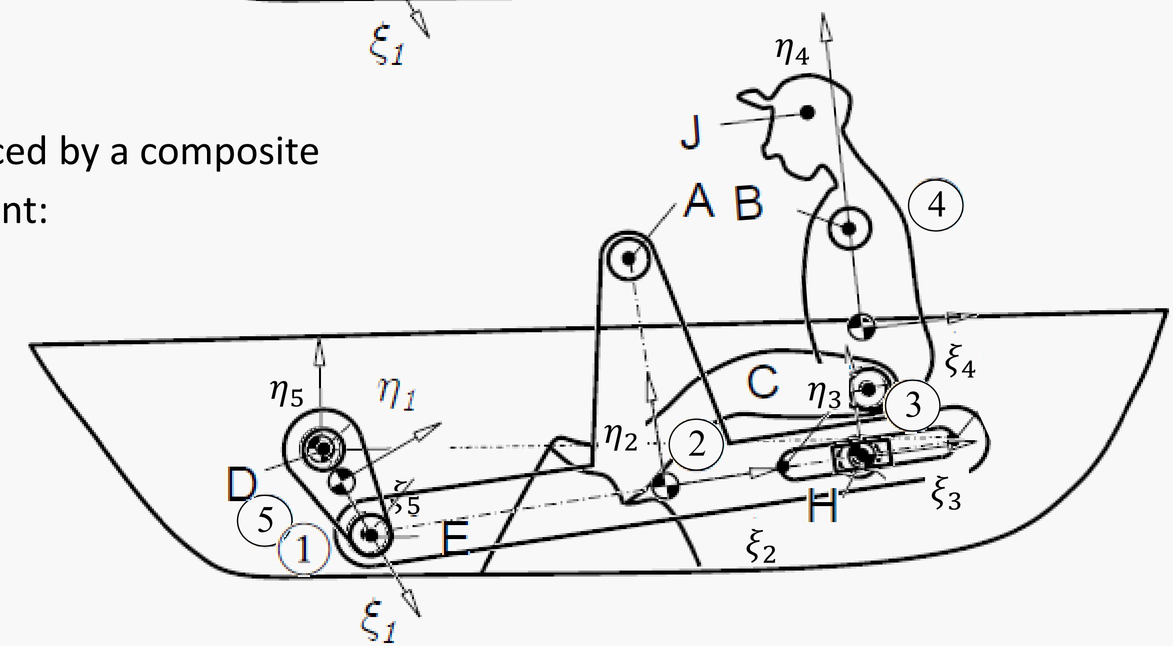
NRevolute – 6

NTranslation – 1

NSimple - 3



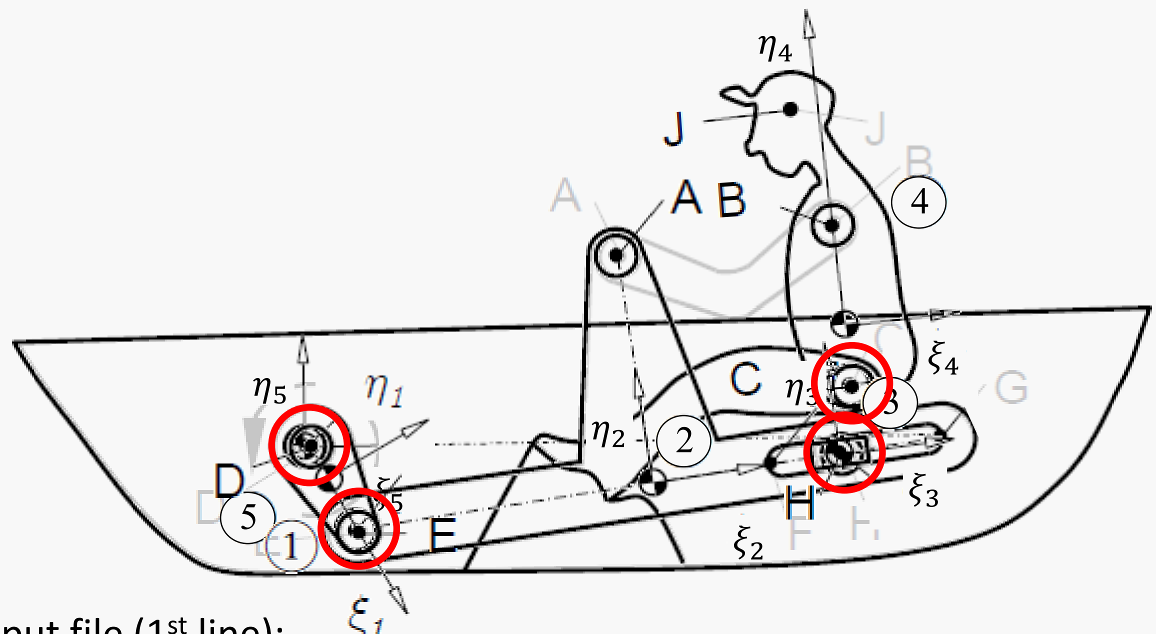
Body 4 can be replaced by a composite revolute-revolute joint:



Dynamics of Mechanical Systems

<u>Application case: Toy rower (Alternative 1)</u>

The toy rower is a mechanical system in which the crank link DE, pinned to the body of the boat, is rotated with a constant angular velocity. The coupler link EAFG, to which the rower has the hands pinned, slides along a body pinned to the boat at point H. The rower, whose upper body is pinned to the boat at point C, has a rocking motion as it rotates about point C, while the arm is pinned to the coupler link at point A. The general dimensions of the mechanical system, shown in the figure, are obtained by a direct measurement of the figure and constant scaling.



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$$l_{BC} = 0.97$$
$$l_{EF} = 2.48$$
$$l_{FG} = 1.02$$
$$l_{CH} = 0.50$$

Input file (1st line):

5 NRevolute NTranslation NRevRev NTraRev Nrigid 0 Nsimple NDriver NPointsOfInt

Dynamics of Mechanical Systems

Application case: Toy rower (Alternative 1)

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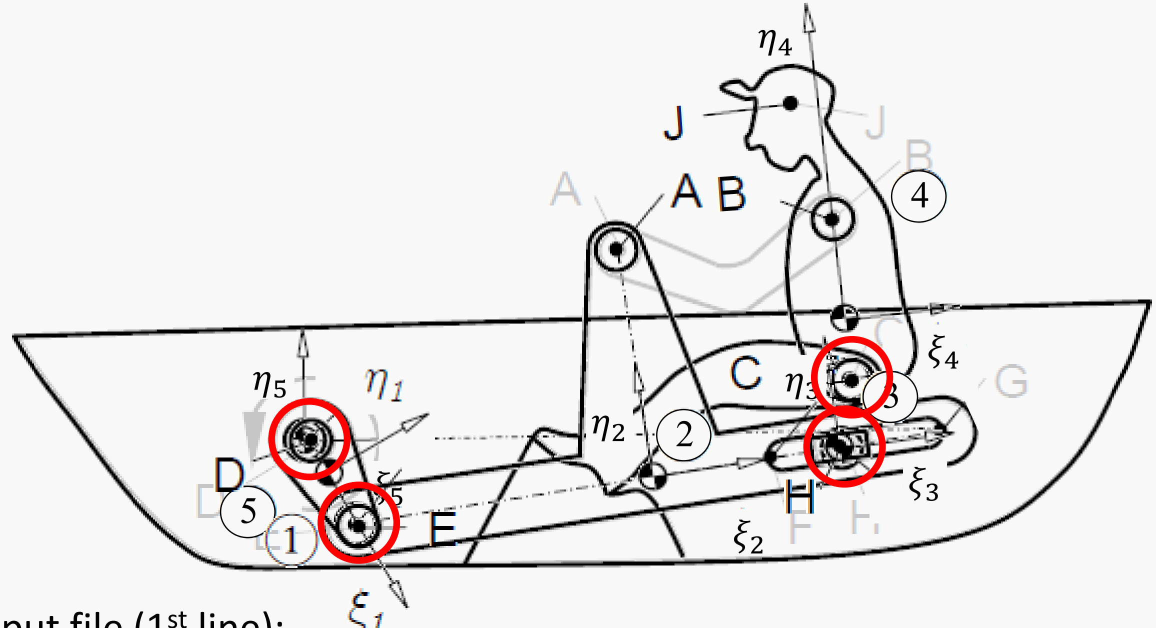

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$$l_{EF} = 2.48$$
$$l_{FG} = 1.02$$
$$l_{CH} = 0.50$$

Input file (1st line):

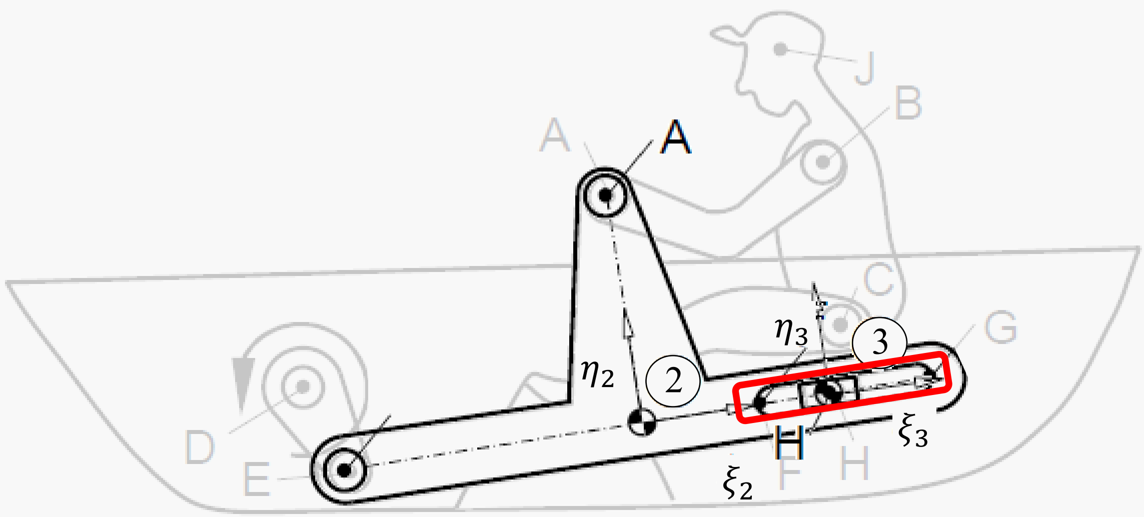
5 4 NTranslation NRevRev NTraRev Nrigid 0 Nsimple NDriver NPointsOfInt

Dynamics of Mechanical Systems

2023/24

Application case: Toy rower (Alternative 1)

The toy rower is a mechanical system in which the crank link DE, pinned to the body of the boat, is rotated with a constant angular velocity. The coupler link EAFG, to which the rower has the hands pinned, slides along a body pinned to the boat at point H. The rower, whose upper body is pinned to the boat at point C, has a rocking motion as it rotates about point C, while the arm is pinned to the coupler link at point A. The general dimensions of the mechanical system, shown in the figure, are obtained by a direct measurement of the figure and constant scaling.



$l_{AB} = 1.30$

$l_{BC} = 0.97$

$l_{EF} = 2.48$

$l_{FG} = 1.02$

$l_{CH} = 0.50$

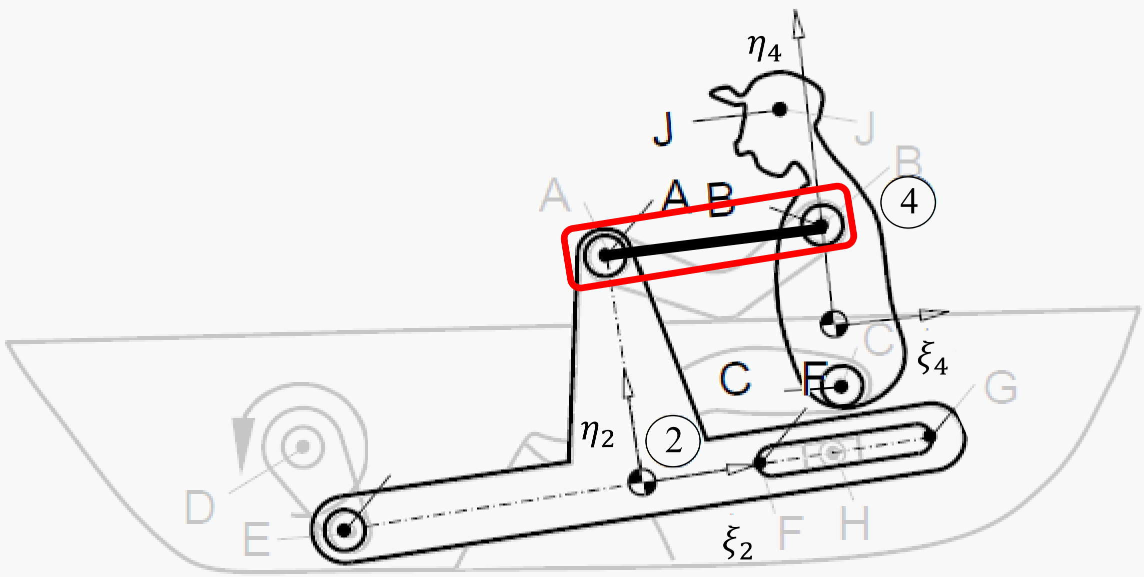
Input file (1st line):

5 4 NTranslation NRevRev NTraRev Nrigid 0 Nsimple NDriver NPointsOfInt

Dynamics of Mechanical Systems

Application case: Toy rower (Alternative 1)

The toy rower is a mechanical system in which the crank link DE, pinned to the body of the boat, is rotated with a constant angular velocity. The coupler link EAFG, to which the rower has the hands pinned, slides along a body pinned to the boat at point H. The rower, whose upper body is pinned to the boat at point C, has a rocking motion as it rotates about point C, while the arm is pinned to the coupler link at point A. The general dimensions of the mechanical system, shown in the figure, are obtained by a direct measurement of the figure and constant scaling.



$l_{AB} = 1.30$

$l_{BC} = 0.97$

$l_{EF} = 2.48$

$l_{FG} = 1.02$

$l_{CH} = 0.50$

Input file (1st line):

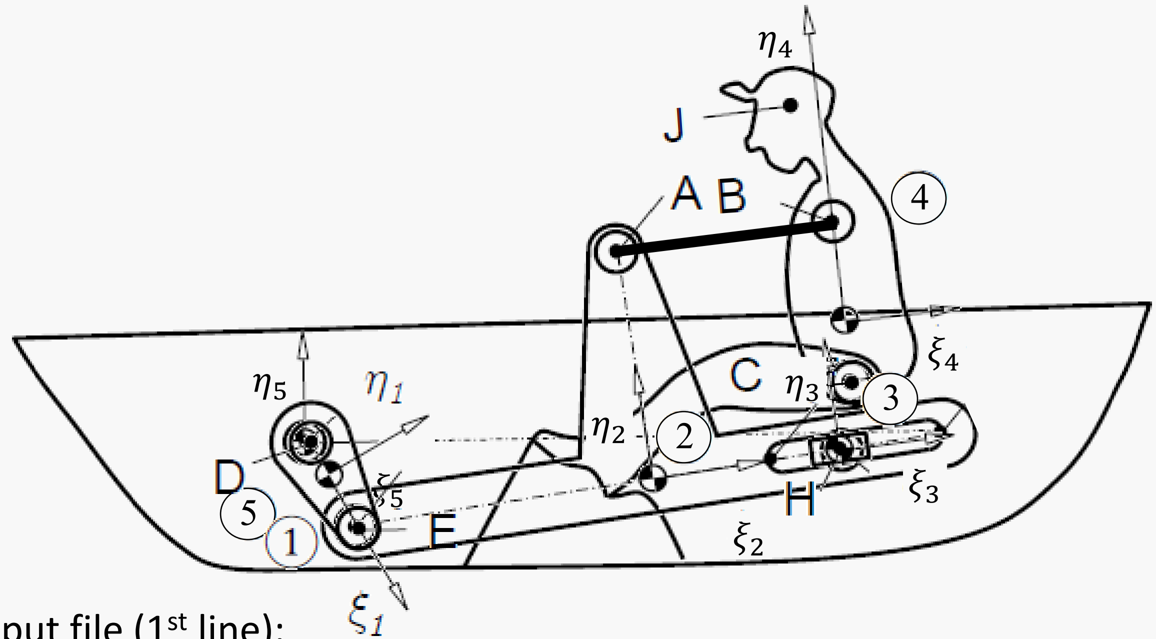
5 4 1 NRevRev NTraRev Nrigid 0 Nsimple NDriver NPointsOfInt

Dynamics of Mechanical Systems

2023/24

Application case: Toy rower (Alternative 1)

The toy rower is a mechanical system in which the crank link DE, pinned to the body of the boat, is rotated with a constant angular velocity. The coupler link EAFG, to which the rower has the hands pinned, slides along a body pinned to the boat at point H. The rower, whose upper body is pinned to the boat at point C, has a rocking motion as it rotates about point C, while the arm is pinned to the coupler link at point A. The general dimensions of the mechanical system, shown in the figure, are obtained by a direct measurement of the figure and constant scaling.



$l_{AB} = 1.30$

$l_{BC} = 0.97$

$l_{EF} = 2.48$

$l_{FG} = 1.02$

$l_{CH} = 0.50$

Input file (1st line):

5 4 1 1 0 0 0 3 1 2

$$n_{dof} = 5 \times 3 - (4 \times 2 + 2 + 1 + 3) = 1$$

Dynamics of Mechanical Systems

Application case: Toy rower (Alternative 1)

Input file:

5 4 1 1 0 0 0 3 1 2
0.150 -0.200 5.236
2.050 -0.230 0.174
3.180 -0.130 0.174
3.200 0.740 0.174
0.000 0.000 0.000
…

1 2 0.360 0.000 -1.780 0.000
4 5 0.000 -0.370 3.250 0.360
3 5 0.000 0.000 3.210 -0.130
1 5 -0.220 0.000 0.000 0.000

Revolute

2 3 0.700 0.000 1.720 0.000 0.000 0.000 1.000 0.000
2 4 1.300 0.000 1.350 0.000 0.600

Rev-Rev

Translation

5 1 0.000
5 2 0.000
5 3 0.000

Ground

1 1 3 0 5.236 -6.2832 0.000 0.000

$$\mathbf{\Phi}^{(d,1)} = \theta_1 - (5.24 - 6.28 \times t)$$

Points of Interest

2 0.000 1.350
5 -0.150 1.320

12 0.0000001
0.000 0.010 2.000

NBody	NRevolute	NTranslation	NRevRev	NTraRev	Nrigid	0	Nsimple	NDriver	NPointsOfInt
5	4	1	1	0	0	0	3	1	2

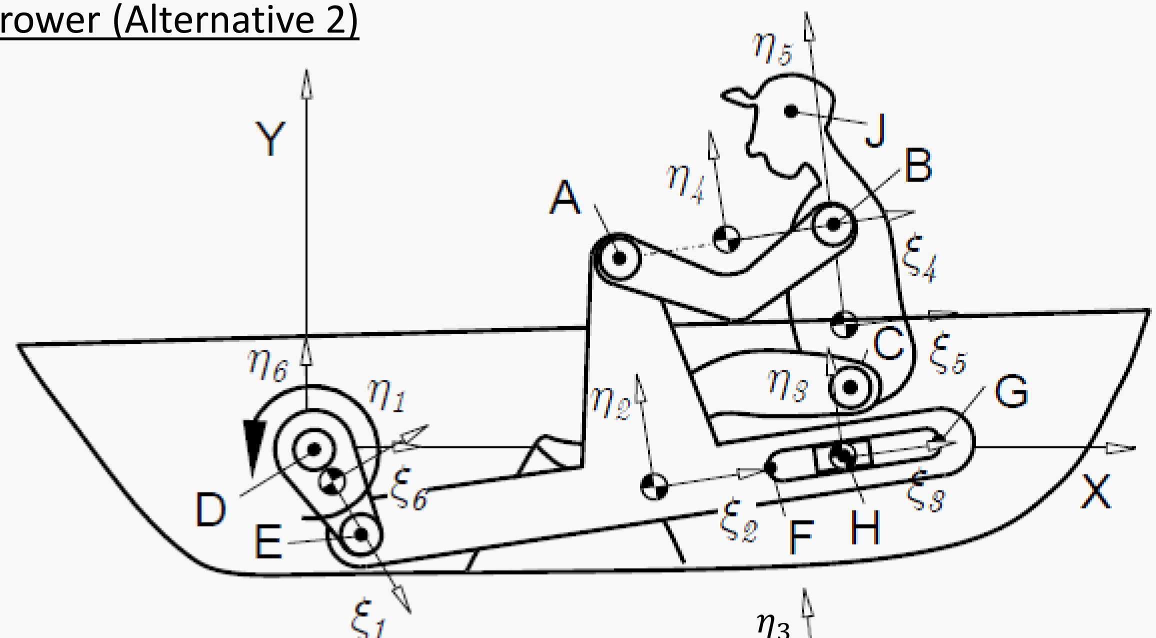
Application case: Toy rower (Alternative 2)

Nbody – 6

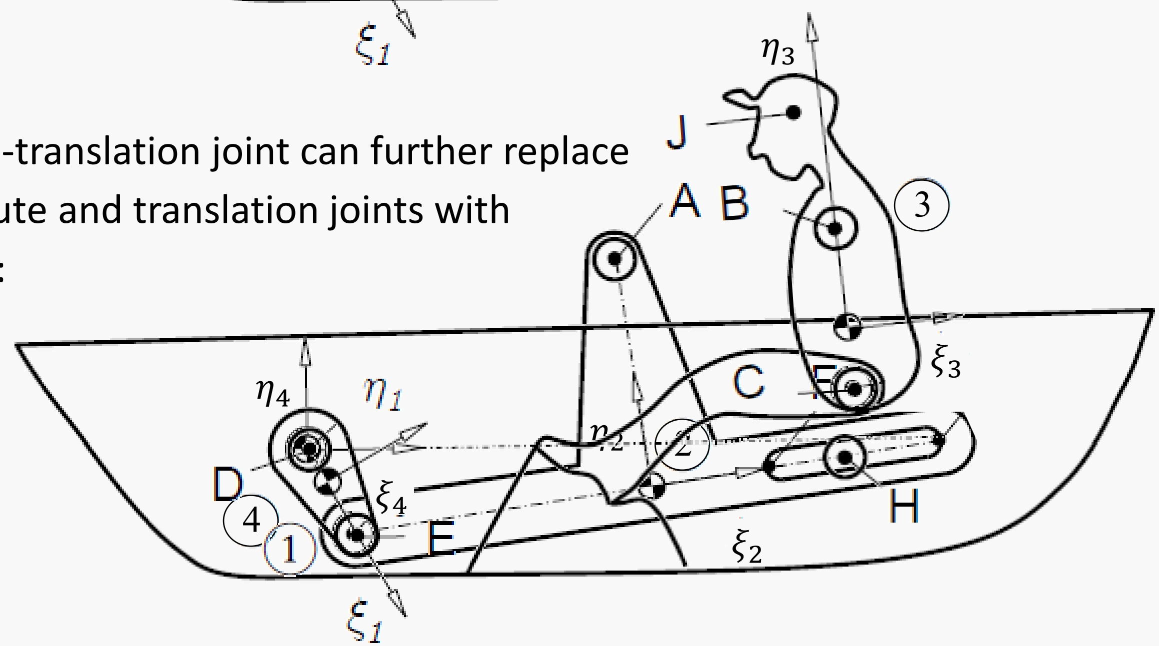
NRevolute – 6

NTranslation – 1

NSimple - 3



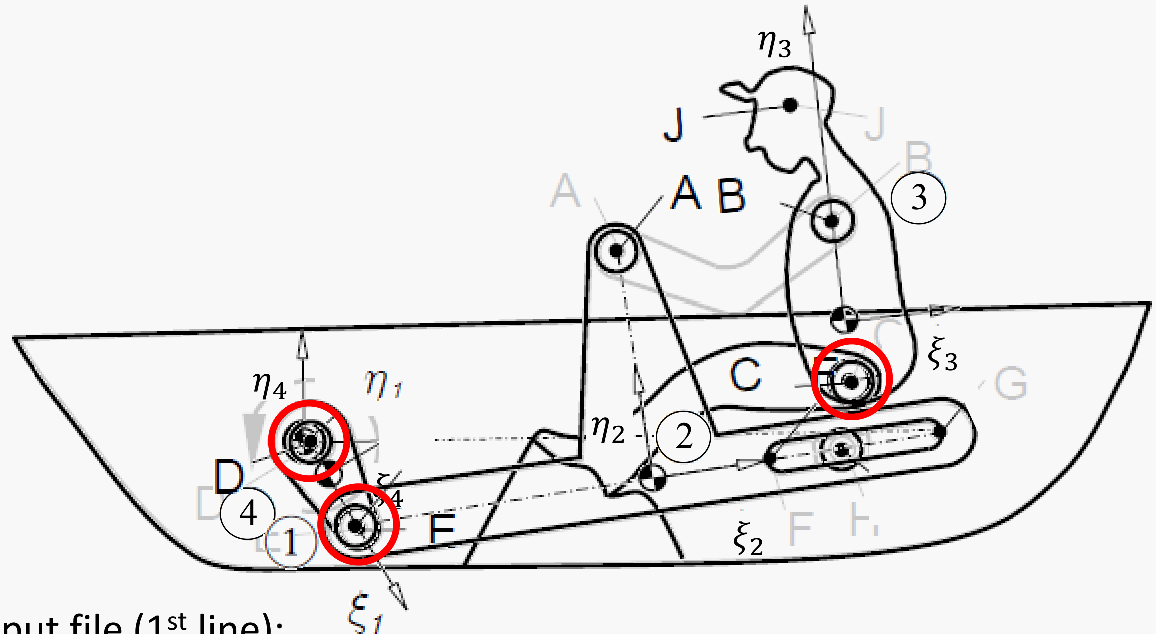
A composite revolute-translation joint can further replace Body 3 and the revolute and translation joints with the boat and coupler:



Dynamics of Mechanical Systems

<u>Application case: Toy rower (Alternative 2)</u>

The toy rower is a mechanical system in which the crank link DE, pinned to the body of the boat, is rotated with a constant angular velocity. The coupler link EAFG, to which the rower has the hands pinned, slides along a body pinned to the boat at point H. The rower, whose upper body is pinned to the boat at point C, has a rocking motion as it rotates about point C, while the arm is pinned to the coupler link at point A. The general dimensions of the mechanical system, shown in the figure, are obtained by a direct measurement of the figure and constant scaling.



$l_{AB} = 1.30$

$l_{BC} = 0.97$

$l_{EF} = 2.48$

$l_{FG} = 1.02$

$l_{CH} = 0.50$

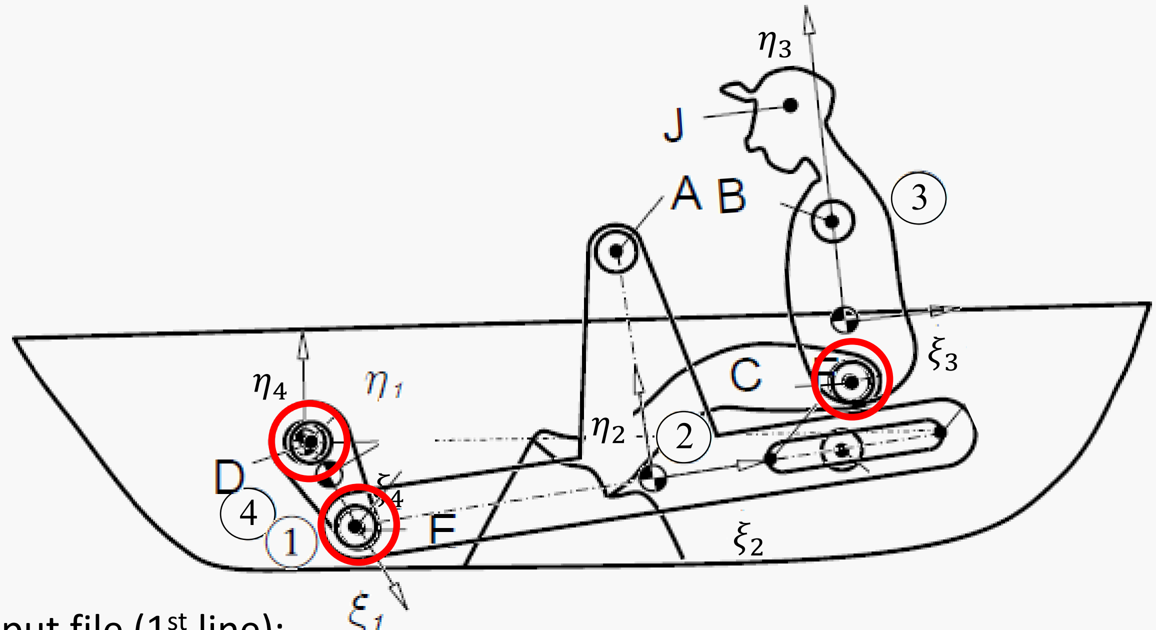
Input file (1st line):

4 NRevolute NTranslation NRevRev NTraRev Nrigid 0 Nsimple NDriver NPointsOfInt

Dynamics of Mechanical Systems 2023/24

Application case: Toy rower (Alternative 2)

The toy rower is a mechanical system in which the crank link DE, pinned to the body of the boat, is rotated with a constant angular velocity. The coupler link EAFG, to which the rower has the hands pinned, slides along a body pinned to the boat at point H. The rower, whose upper body is pinned to the boat at point C, has a rocking motion as it rotates about point C, while the arm is pinned to the coupler link at point A. The general dimensions of the mechanical system, shown in the figure, are obtained by a direct measurement of the figure and constant scaling.



$l_{AB} = 1.30$

$l_{BC} = 0.97$

$l_{EF} = 2.48$

$l_{FG} = 1.02$

$l_{CH} = 0.50$

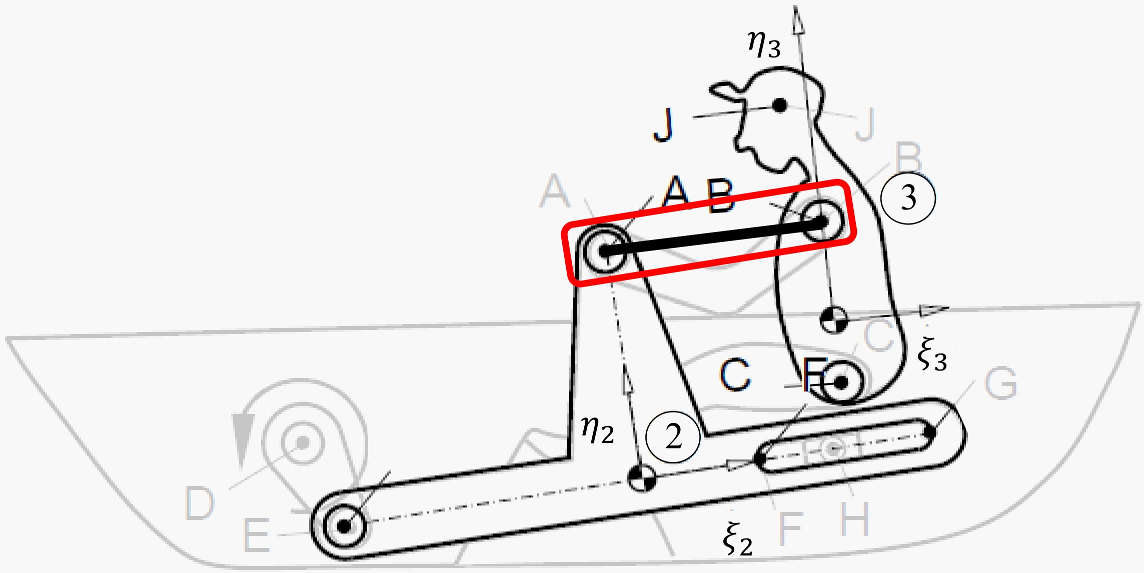
Input file (1st line):

4 3 NTranslation NRevRev NTraRev Nrigid 0 Nsimple NDriver NPointsOfInt

Dynamics of Mechanical Systems

Application case: Toy rower (Alternative 2)

The toy rower is a mechanical system in which the crank link DE, pinned to the body of the boat, is rotated with a constant angular velocity. The coupler link EAFG, to which the rower has the hands pinned, slides along a body pinned to the boat at point H. The rower, whose upper body is pinned to the boat at point C, has a rocking motion as it rotates about point C, while the arm is pinned to the coupler link at point A. The general dimensions of the mechanical system, shown in the figure, are obtained by a direct measurement of the figure and constant scaling.



$l_{AB} = 1.30$

$l_{BC} = 0.97$

$l_{EF} = 2.48$

$l_{FG} = 1.02$

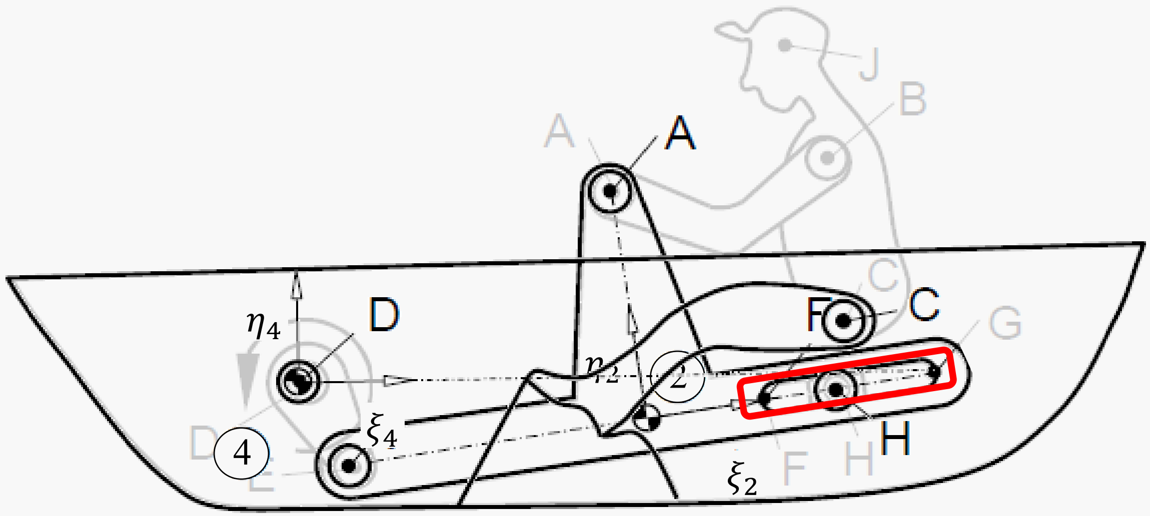
$l_{CH} = 0.50$

Input file (1st line):

4 3 0 NRevRev NTraRev Nrigid 0 Nsimple NDriver NPointsOfInt

Application case: Toy rower (Alternative 2)

The toy rower is a mechanical system in which the crank link DE, pinned to the body of the boat, is rotated with a constant angular velocity. The coupler link EAFG, to which the rower has the hands pinned, slides along a body pinned to the boat at point H. The rower, whose upper body is pinned to the boat at point C, has a rocking motion as it rotates about point C, while the arm is pinned to the coupler link at point A. The general dimensions of the mechanical system, shown in the figure, are obtained by a direct measurement of the figure and constant scaling.



$l_{AB} = 1.30$

$l_{BC} = 0.97$

$l_{EF} = 2.48$

$l_{FG} = 1.02$

$l_{CH} = 0.50$

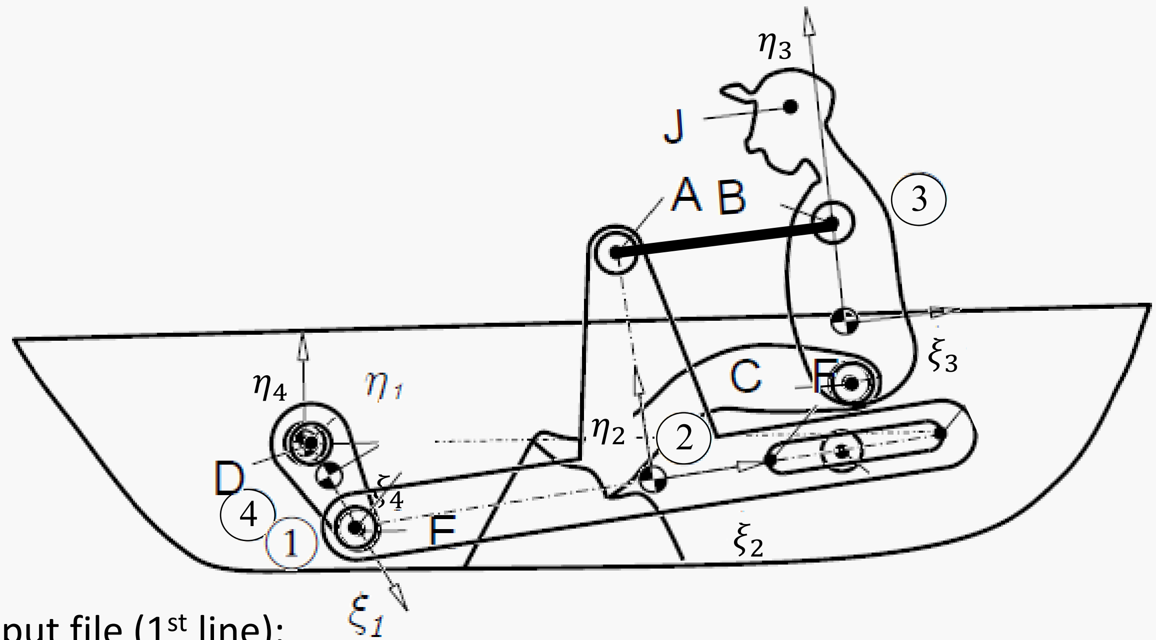
Input file (1st line):

4 3 0 1 NTraRev Nrigid 0 Nsimple NDriver NPointsOfInt

MuboKAP Application Case

Application case: Toy rower (Alternative 2)

The toy rower is a mechanical system in which the crank link DE, pinned to the body of the boat, is rotated with a constant angular velocity. The coupler link EAFG, to which the rower has the hands pinned, slides along a body pinned to the boat at point H. The rower, whose upper body is pinned to the boat at point C, has a rocking motion as it rotates about point C, while the arm is pinned to the coupler link at point A. The general dimensions of the mechanical system, shown in the figure, are obtained by a direct measurement of the figure and constant scaling.



$l_{AB} = 1.30$

$l_{BC} = 0.97$

$l_{EF} = 2.48$

$l_{FG} = 1.02$

$l_{CH} = 0.50$

Input file (1st line):

4 3 0 1 1 0 0 3 1 2

$$n_{dof} = 4 \times 3 - (3 \times 2 + 1 + 1 + 3) = 1$$

Dynamics of Mechanical Systems

Application case: Toy rower (Alternative 2)

Input file:
4 3 0 1 1 0 0 3 1 2
0.150 -0.200 5.236
2.050 -0.230 0.174
3.200 0.740 0.174
0.000 0.000 0.000
…

1 2 0.360 0.000 -1.780 0.000
3 4 0.000 -0.370 3.250 0.360
1 4 -0.220 0.000 0.000 0.000
(Revolute)

2 3 1.300 0.000 1.350 0.000 0.600 (Rev-Rev)

4 2 0.000 3.210 -0.130 0.700 0.000 1.720 0.000 (Trans-Rev)

4 1 0.000
4 2 0.000
4 3 0.000
(Ground)

1 1 3 0 5.236 -6.2832 0.000 0.000

$$\mathbf{\Phi}^{(d,1)} = \theta_1 - (5.24 - 6.28 \times t)$$

Points of Interest:
2 0.000 1.350
3 -0.150 1.320

12 0.0000001
0.000 0.010 2.000

NBody	NRevolute	NTranslation	NRevRev	NTraRev	Nrigid	0	Nsimple	NDriver	NPointsOfInt
4	3	0	1	1	0	0	3	1	2