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FACULTY OF ENGINEERING
AND ARCHITECTURE

DEPARTMENT OF ELECTRICAL ENERGY, METALS, MECHANICAL CONSTRUCTION AND ENGINEERING
RESEARCH GROUP DYNAMICAL SYSTEMS AND CONTROL (DYSC)

VIRTUAL DRIVELINE DESIGN THROUGH CO-SIMULATION

David van Os / Conference day 28-05-2019

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CONTENT

- Introduction
- General workflow for virtual driveline optimization
- Challenges and requirements of Ball juggler V2
- Determination of design parameters with co-simulations
- Motor selection
- Controller tuning and torque feedforward

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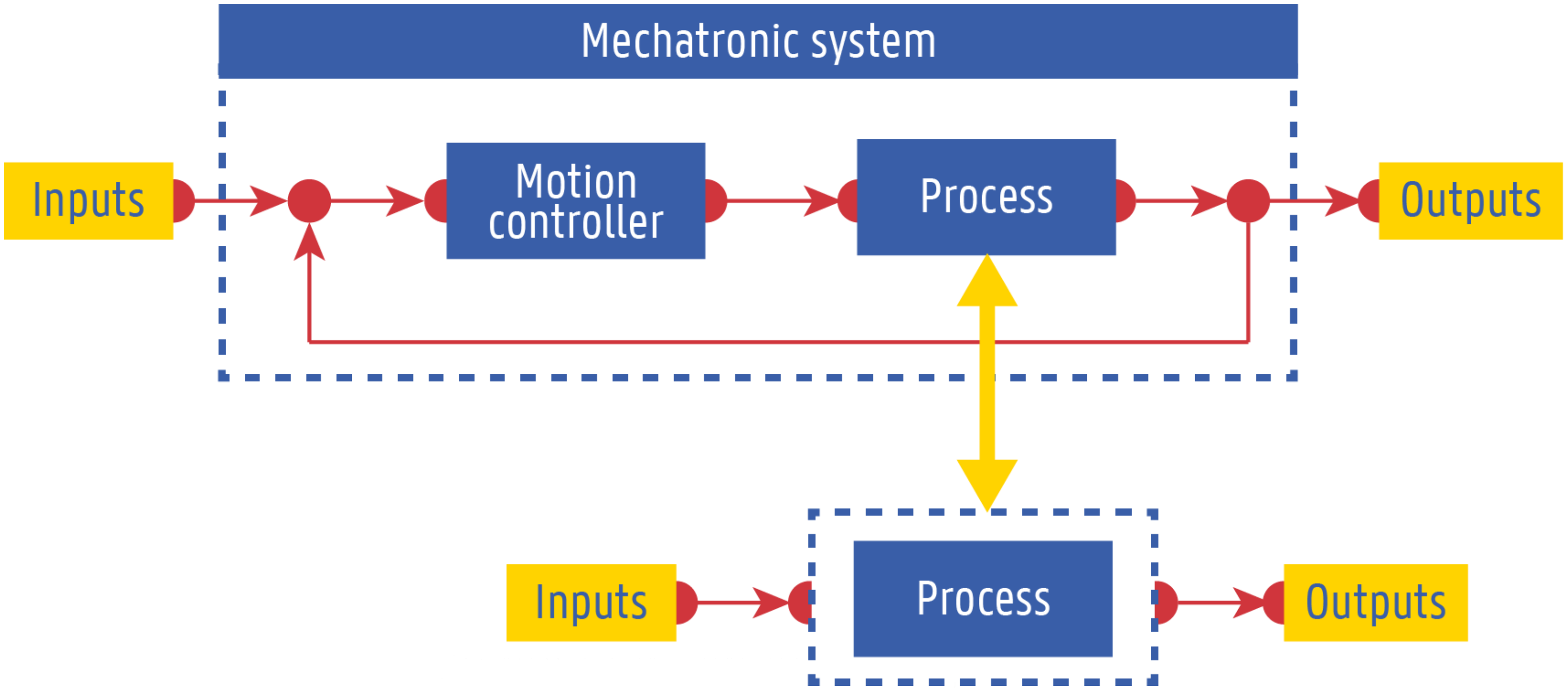
INTRODUCTION

THE NEED FOR A CO-SIMULATION

- A mechatronic system is a multi-domain system
- The subsystems are modelled and simulated with domain specific software
  - Process: Siemens NX
  - Motion controller: Matlab/Simulink
- Global simulation in done by simulating the subsystems in a black-box manner
- Co-simulations allow data-exchange between coupled systems



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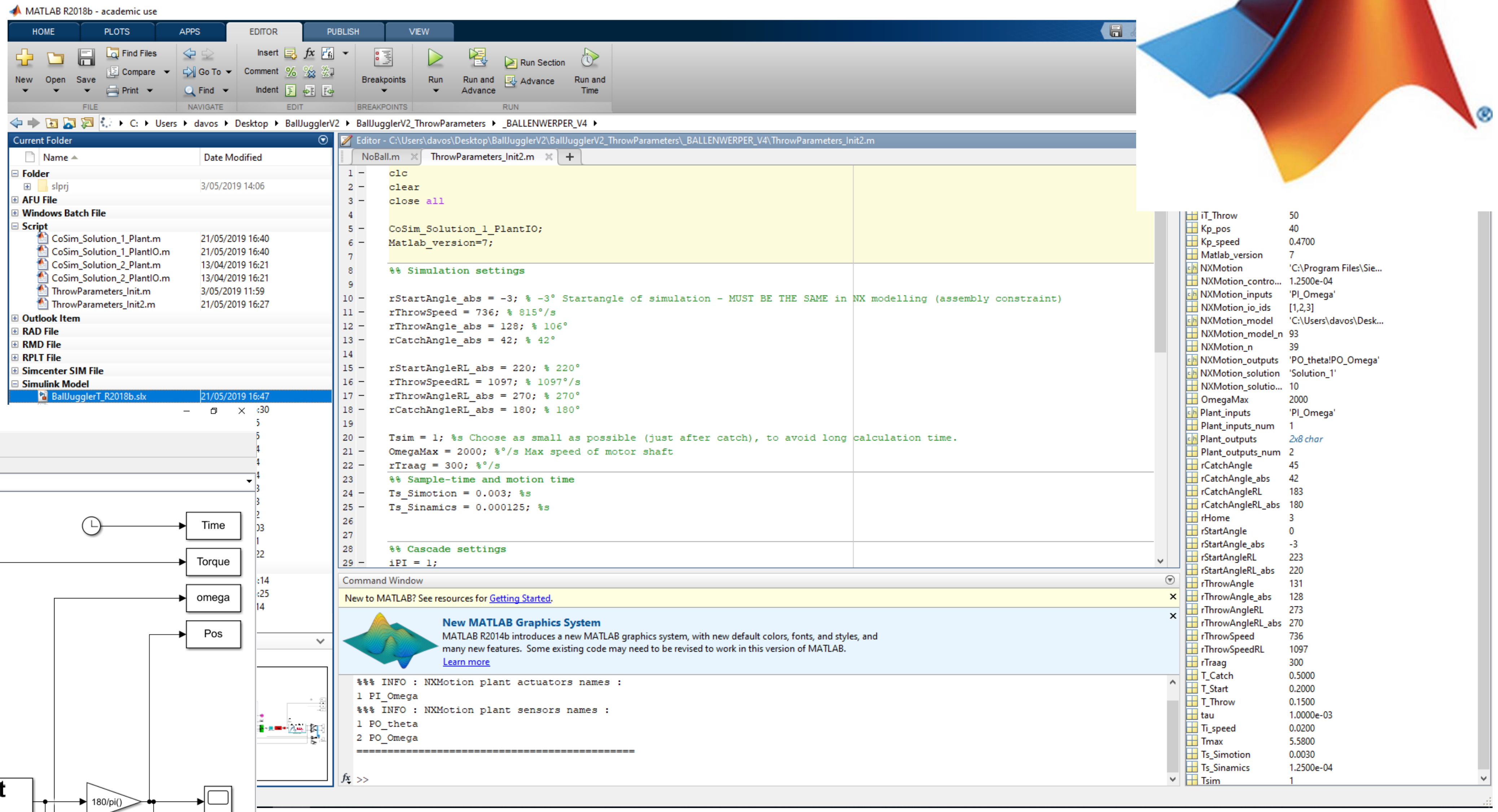
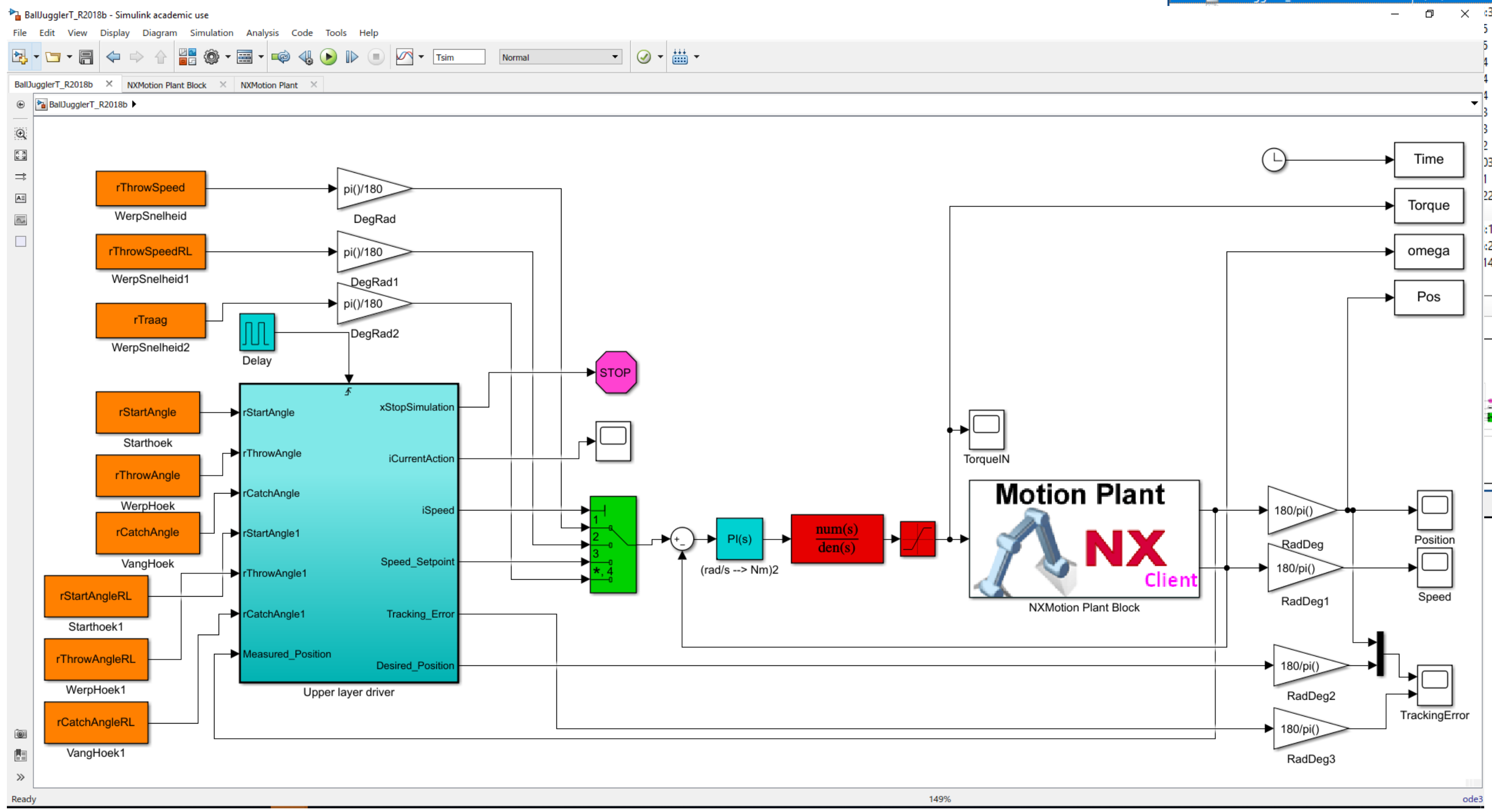
SOFTWARE: MATLAB/SIMULINK

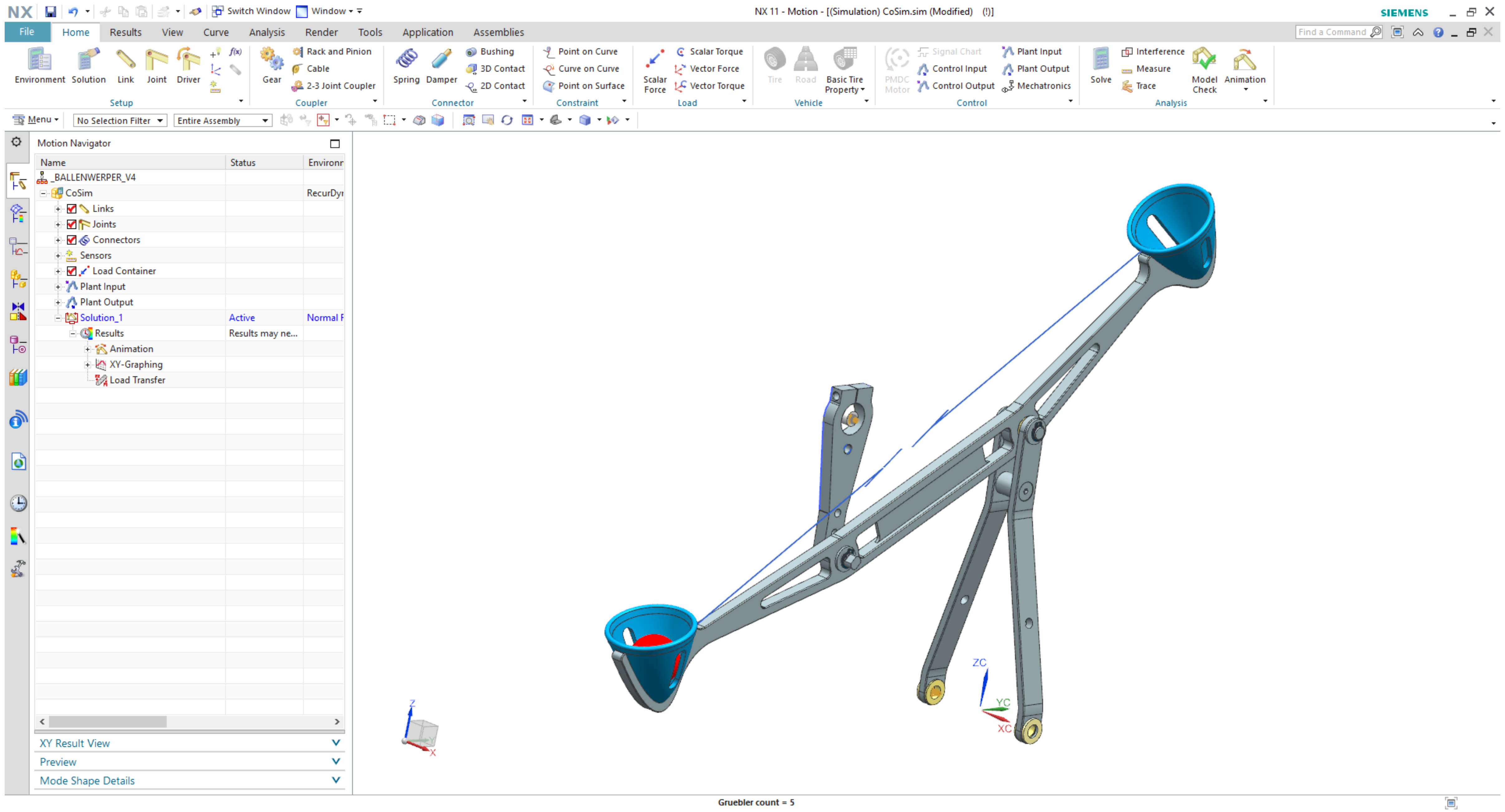
- Numerical computing environment
- Simulink: model based design
  - Simulation of systems
  - Code generation





SOFTWARE: SIEMENS NX

- CAD/CAE/CAM software
- Design of mechanical systems
- Engineering environment
  - E.g. Motion simulation
  - E.g. FEM, CFD analysis
- Manufacturing



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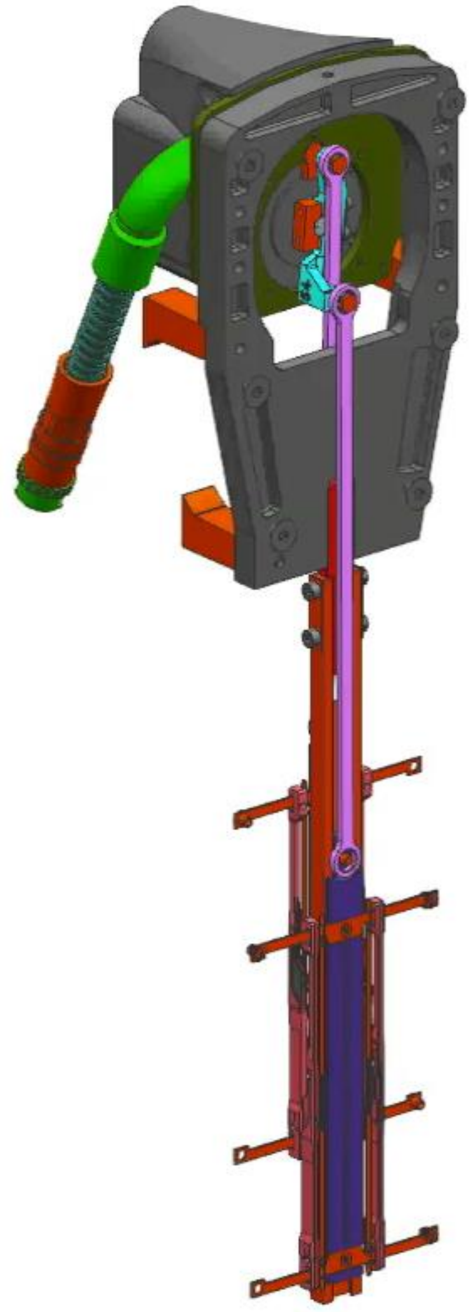
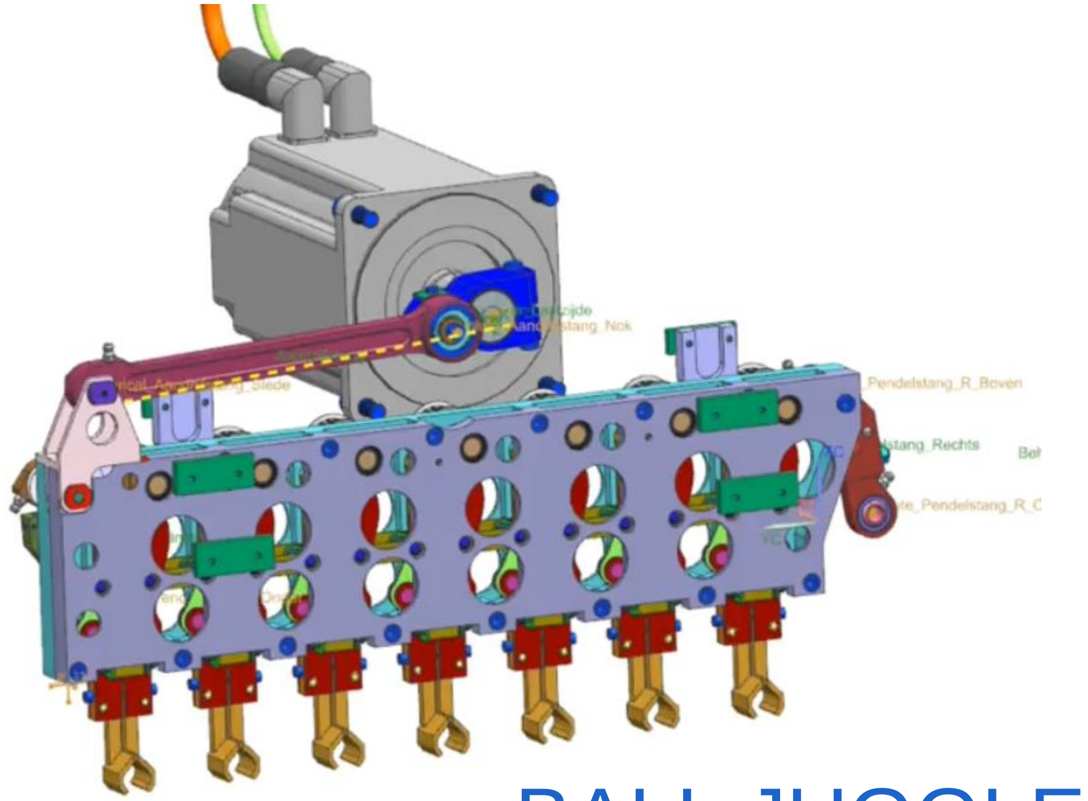
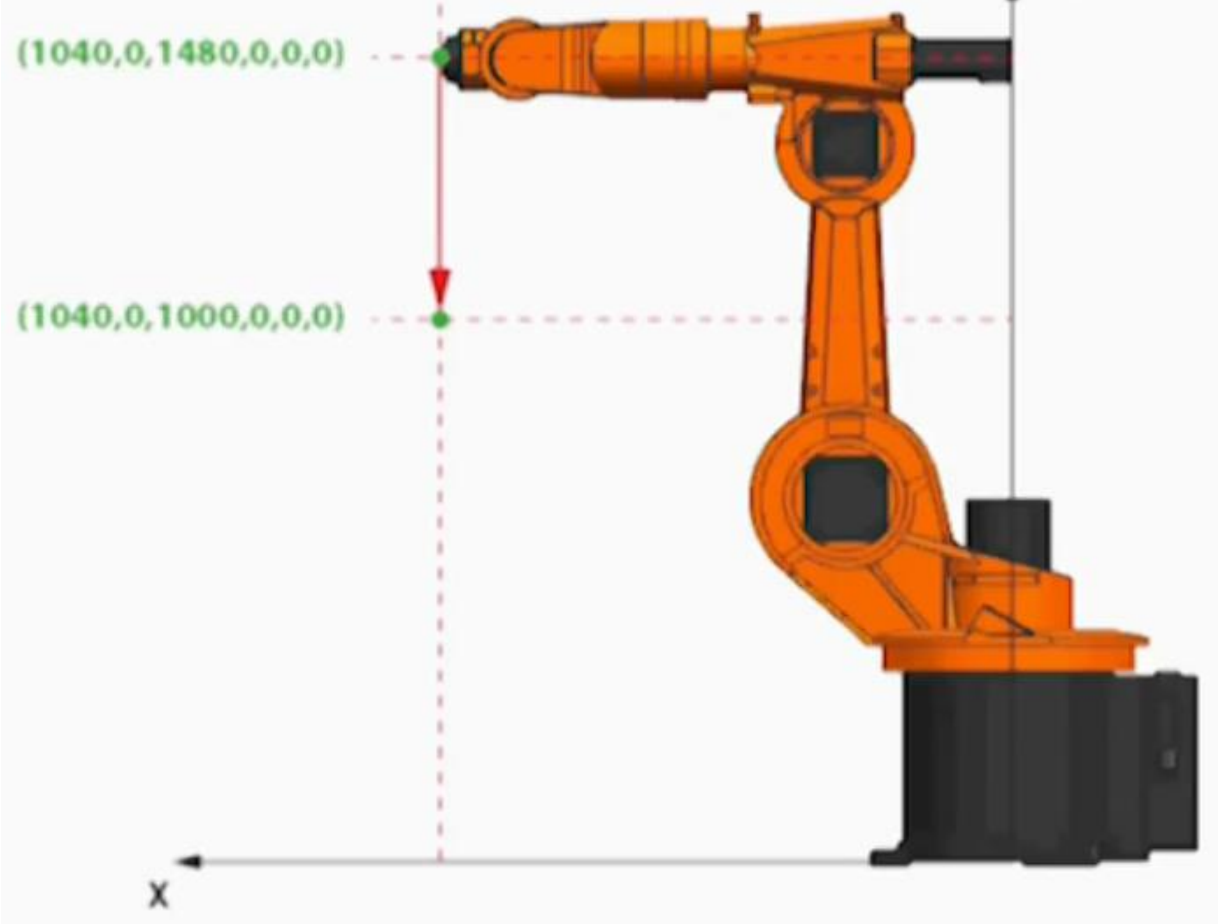
WEAVING UNIT



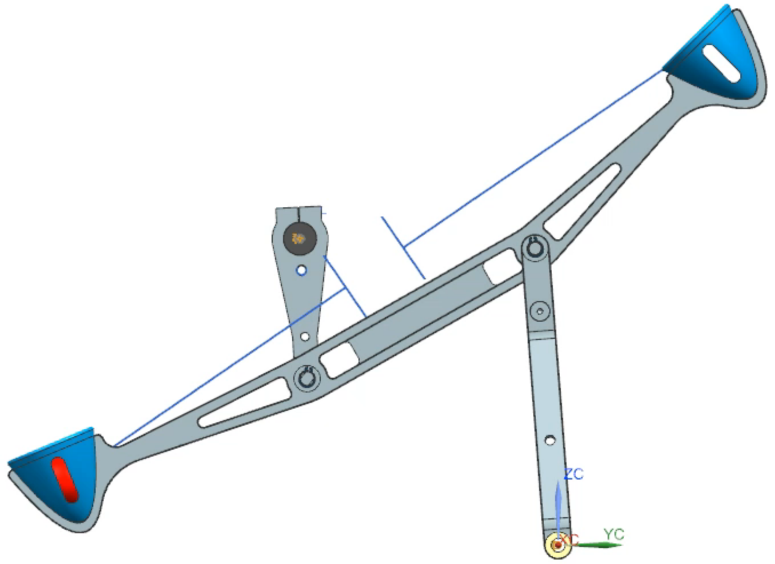
PICK & PLACE UNIT



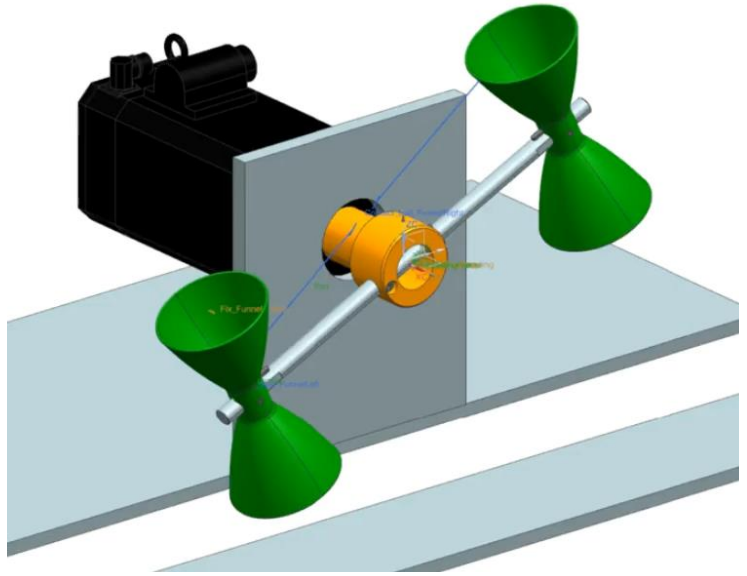
6 DOF ROBOT



BALL JUGGLER V2



BALL JUGGLER V1



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VIRTUAL DRIVELINE OPTIMIZATION

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WORKFLOW

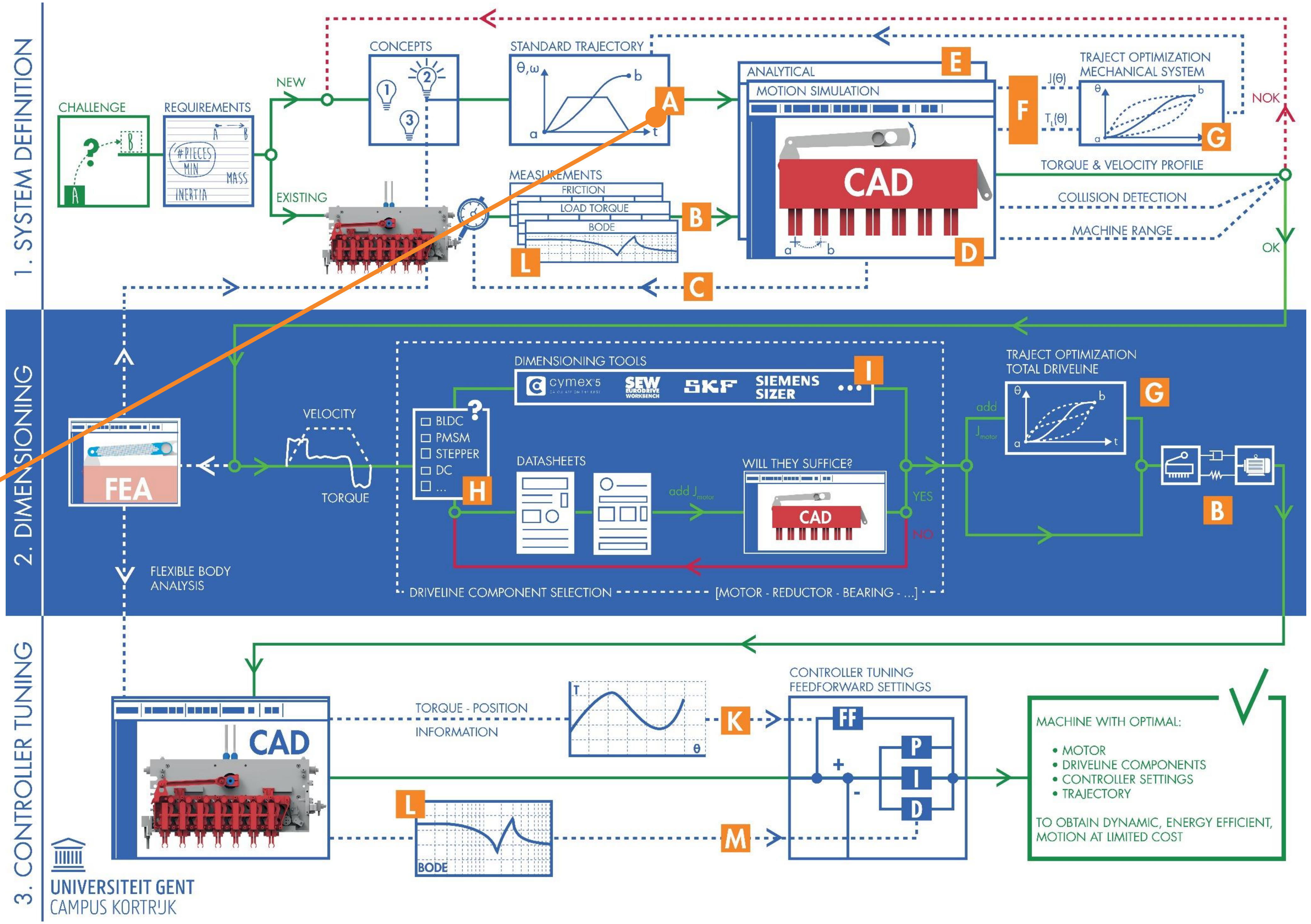
- Workflow for virtual driveline optimization
- Achieve a machine with optimal:
  - Motor
  - Driveline components
  - Controller settings
  - Trajectory
- The advantage of CAD-tools and cosimulations are fully used

Guidelines & presentations

How-to video's

Excel calculation sheets

Matlab/Octave scripts



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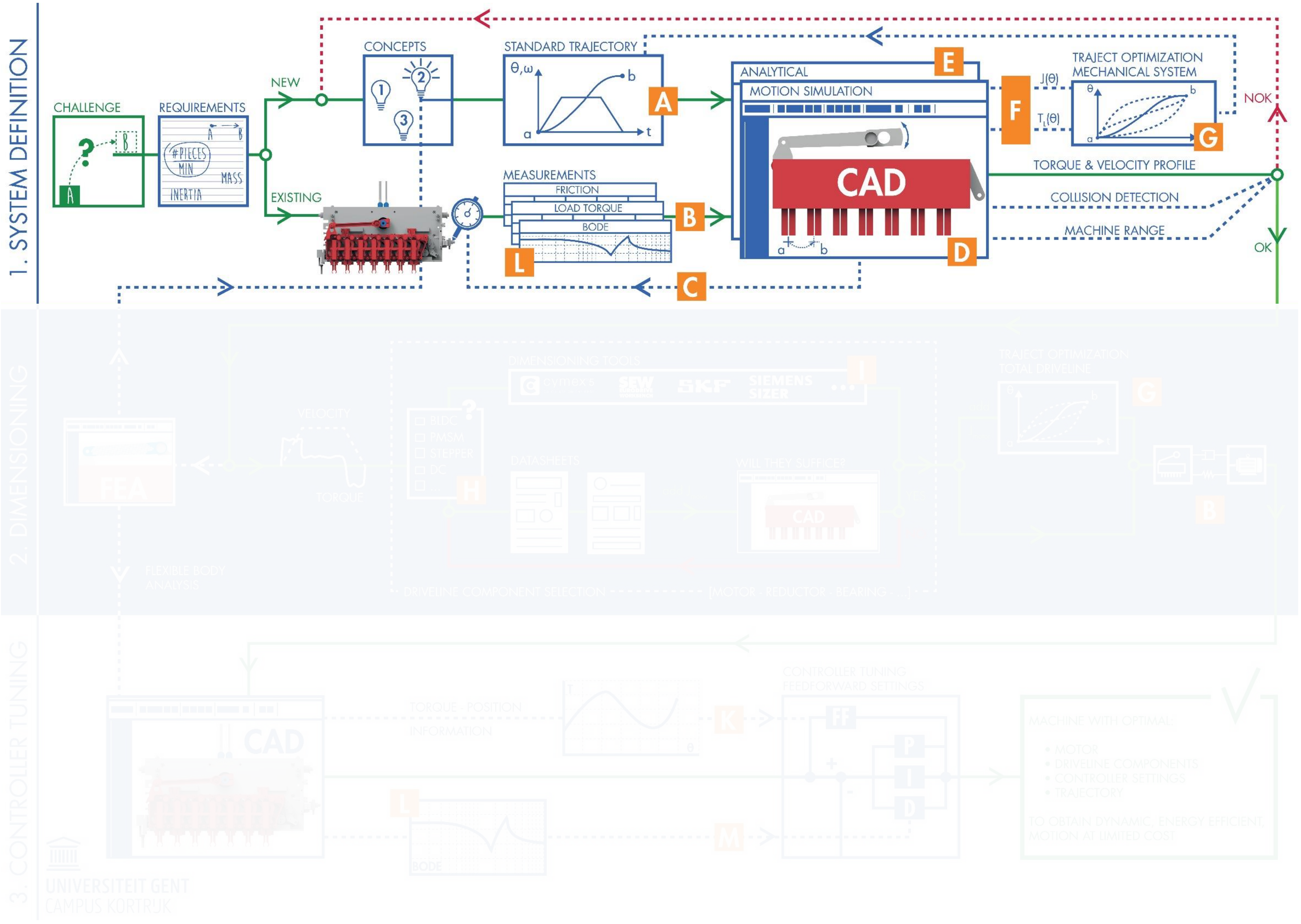
WORKFLOW

- Three main topics
- 1) system definition
    - Challenge, requirements, concepts
    - Fit model to reality
    - Extract data from model
    - Trajectory definition



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WORKFLOW

- Three main topics
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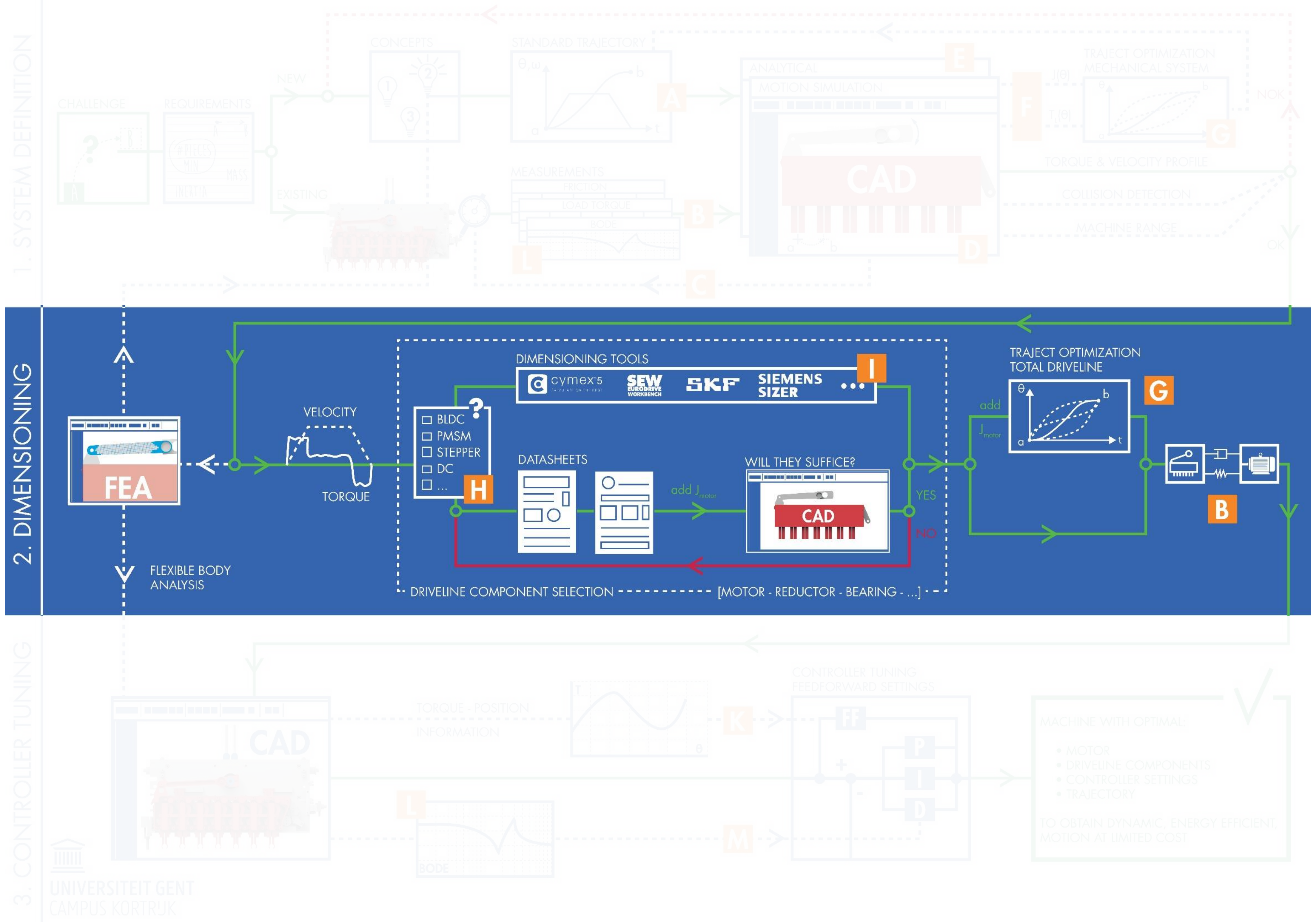
  - Trajectory definition
- 2) Dimensioning
  - Motor selection (add motor inertia)
  - Include flexibility in model



WORKFLOW

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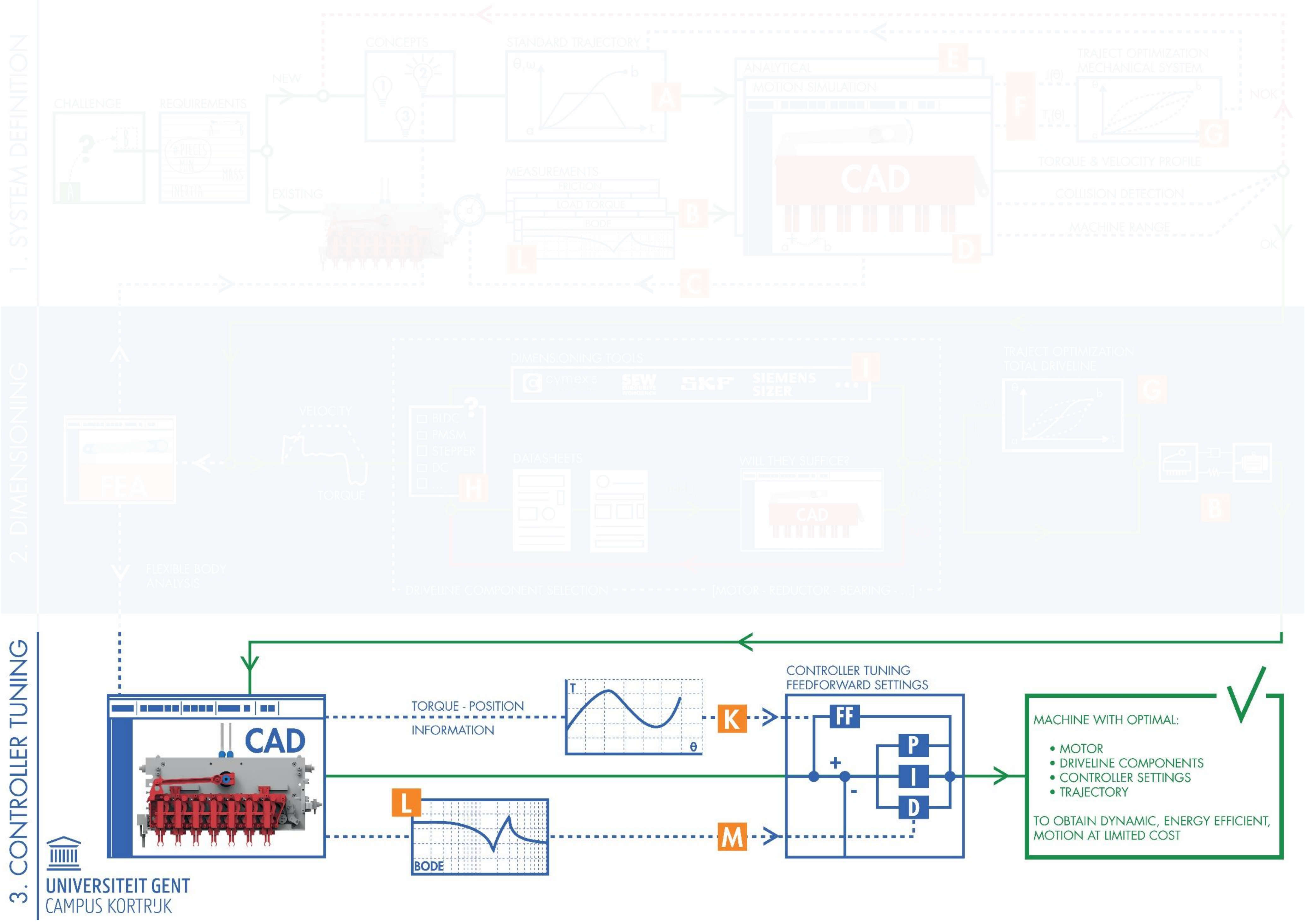
  - Extract data from model
  - Trajectory definition
- 2) Dimensioning
  - Motor selection (add motor inertia)
  - Include flexibility in model
- 3) Controller tuning
  - Tuning of common cascade controller
  - Expanding the common cascade controller



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MODELLING THE MECHATRONIC SYSTEM

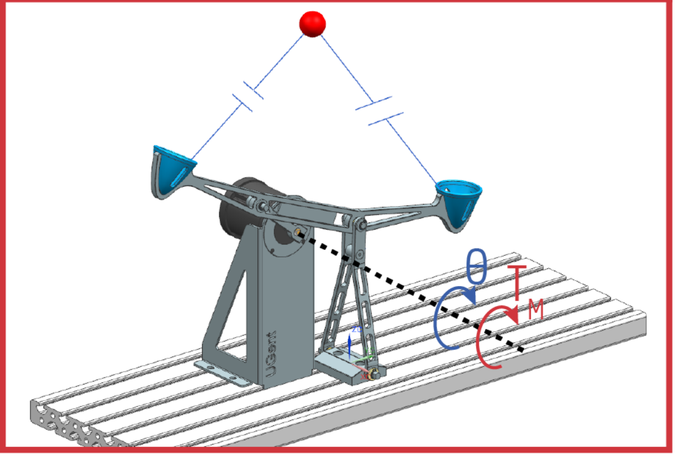
MODELLING THE PROCESS

- Available data after modelling in CAD:
  - Mass/inertia of links
  - Flexibility of links (flexible body analysis)
  - Mechanic tolerance, …

Collection of data:

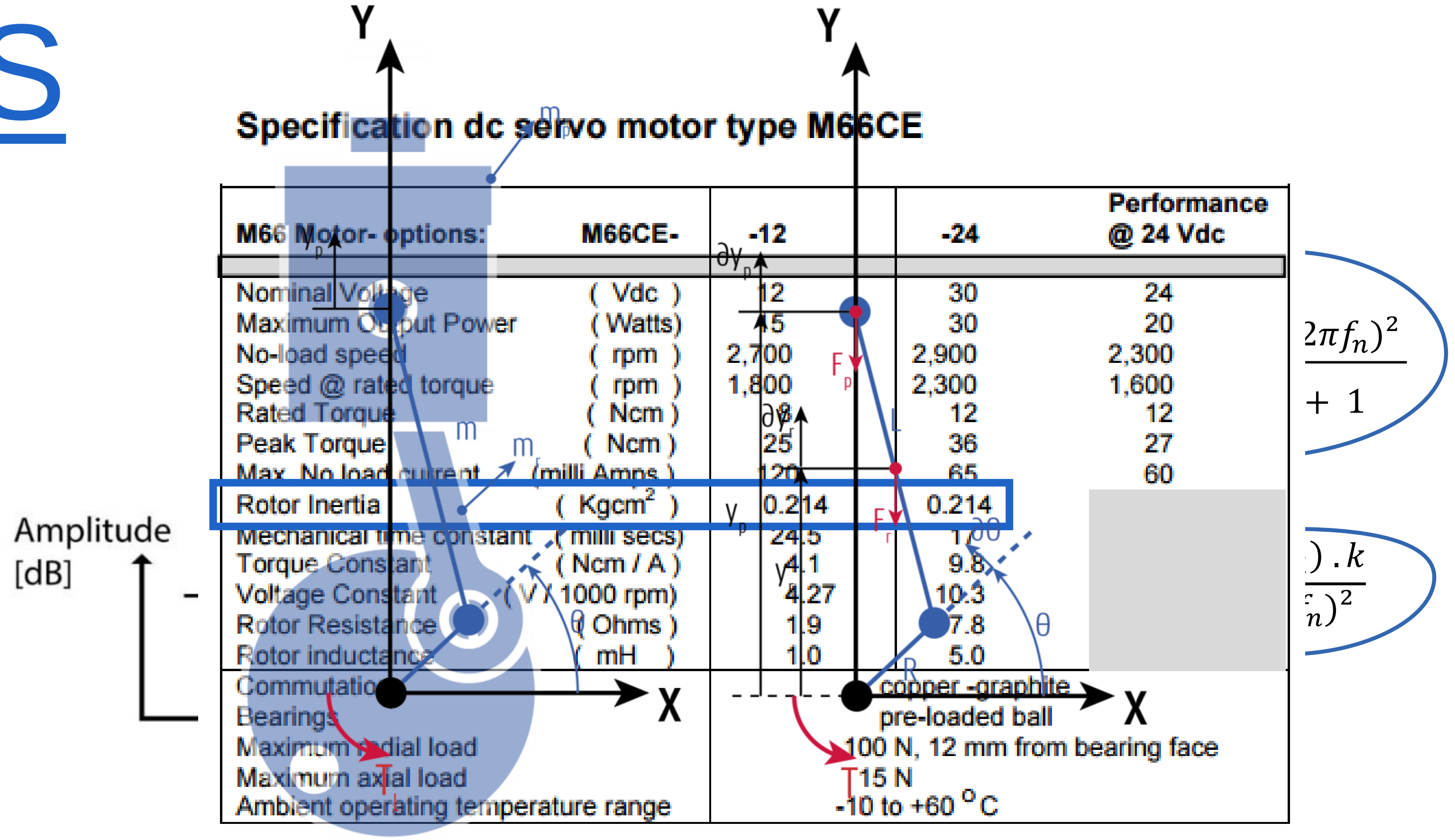
- Friction
- Flexibility and damping
- External process forces
- Motor inertia
- …

Virtual model in Siemens NX



MODELLING THE PROCESS

- Motion features allow the user to add more data
  - E.g. determination of flexibility and damping out of bode
  - E.g. motor inertia in datasheet
  - E.g. calculation of load torque



M66 Motor- options:	M66CE-	-12	-24	Performance @ 24 Vdc
Nominal Voltage	(Vdc)	12	30	24
Maximum Output Power	(Watts)	15	30	20
No-load speed	(rpm)	2,700	2,900	2,300
Speed @ rated torque	(rpm)	1,800	2,300	1,600
Rated Torque	(Ncm)	8	12	12
Peak Torque	(Ncm)	25	36	27
Max. No load current	(milli Amps)	120	65	60
Rotor Inertia	($Kgcm^2$)	0.214	0.214	
Mechanical time constant	(milli secs)	24.5	17.0	
Torque Constant	(Ncm / A)	4.1	9.8	
Voltage Constant	(V / 1000 rpm)	4.27	10.3	
Rotor Resistance	(Ohms)	1.9	7.8	
Rotor inductance	(mH)	1.0	5.0	
Commutation		copper -graphite		
Bearings		pre-loaded ball		
Maximum radial load		100 N, 12 mm from bearing face		
Maximum axial load		15 N		
Ambient operating temperature range		-10 to +60 °C		

Real machine or prototype available?

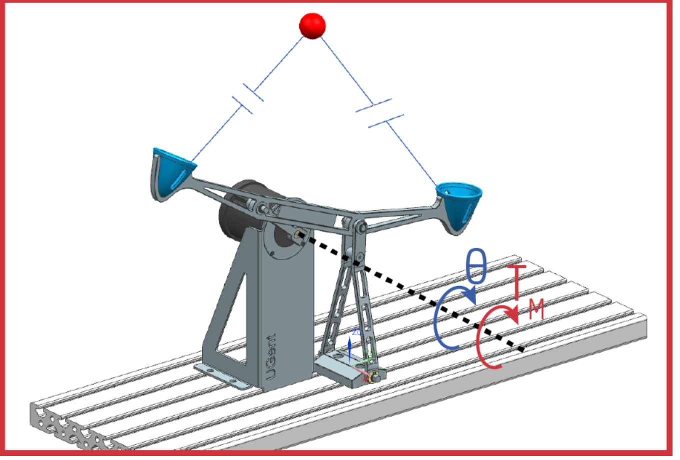
Yes → Measurements

No → Data sheets / Previous knowledge / Calculations

Collection of data:

- Friction
- Flexibility and damping
- External process forces
- Motor inertia
- …

Virtual model in Siemens NX



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MODELLING THE PROCESS

- Before implementing the process in the total mechatronic system, validation can be done
- Validation is only possible if a real machine or prototype is available

Real machine or prototype available?

Yes

No

Measurements

Data sheets
Previous knowledge
Calculations

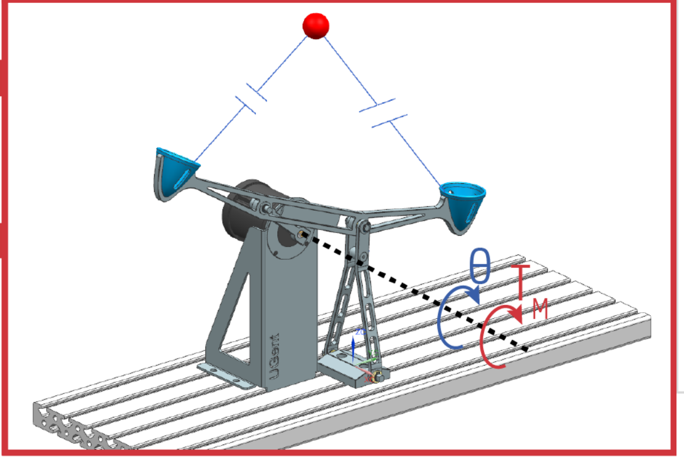
Collection of data:

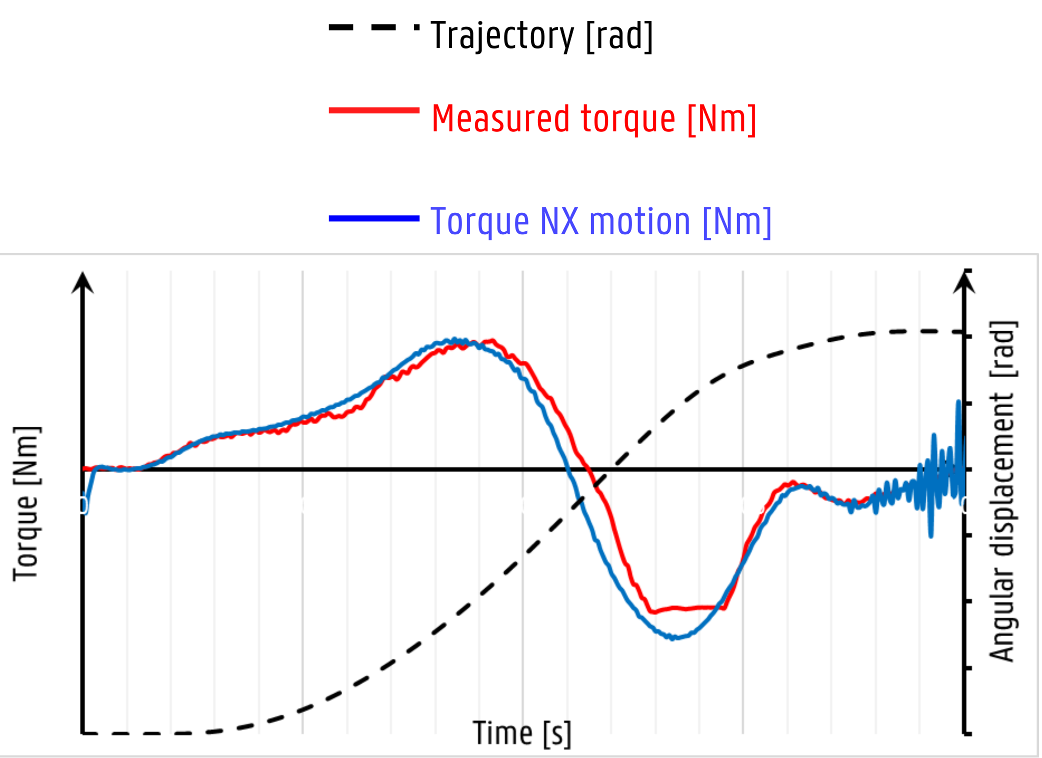
- Friction
- Flexibility and damping
- External process forces
- Motor inertia
- …

Validation of the model

- Bode
- Torque measurement
- …

Virtual model in Siemens NX





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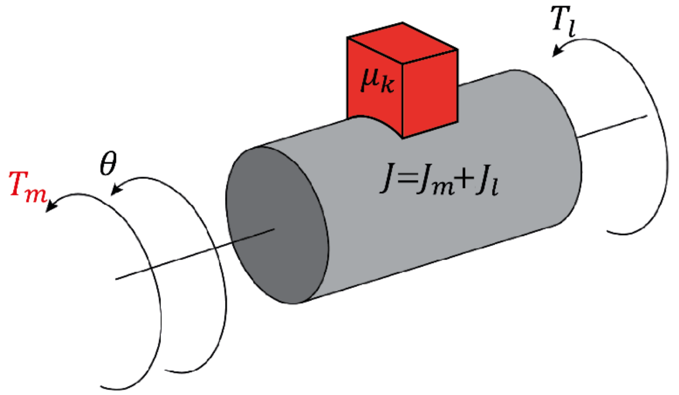
EXTRACTING DATA

- Once the virtual model in well-fitted to reality, important data can be extracted that is needed for further design of the total driveline:
  - Motor selection
  - Trajectory optimization
  - Controller tuning/expanding

$$T_m = T_l + \mu_k \dot{\theta} + \frac{1}{2}\frac{dJ}{d\theta}\left(\dot{\theta}\right)^2 + J\ddot{\theta}$$



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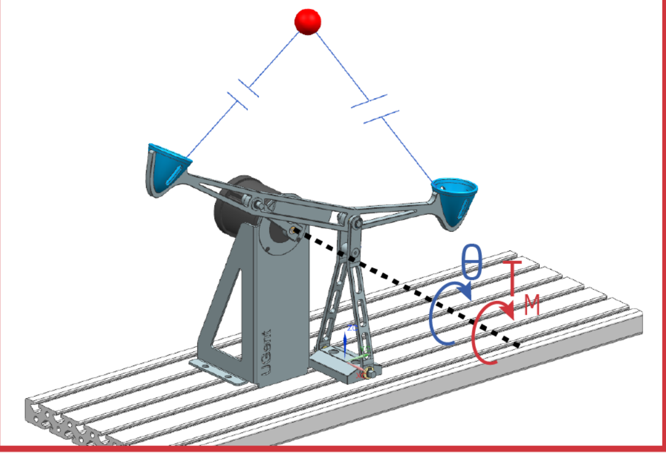
Virtual model in Siemens NX

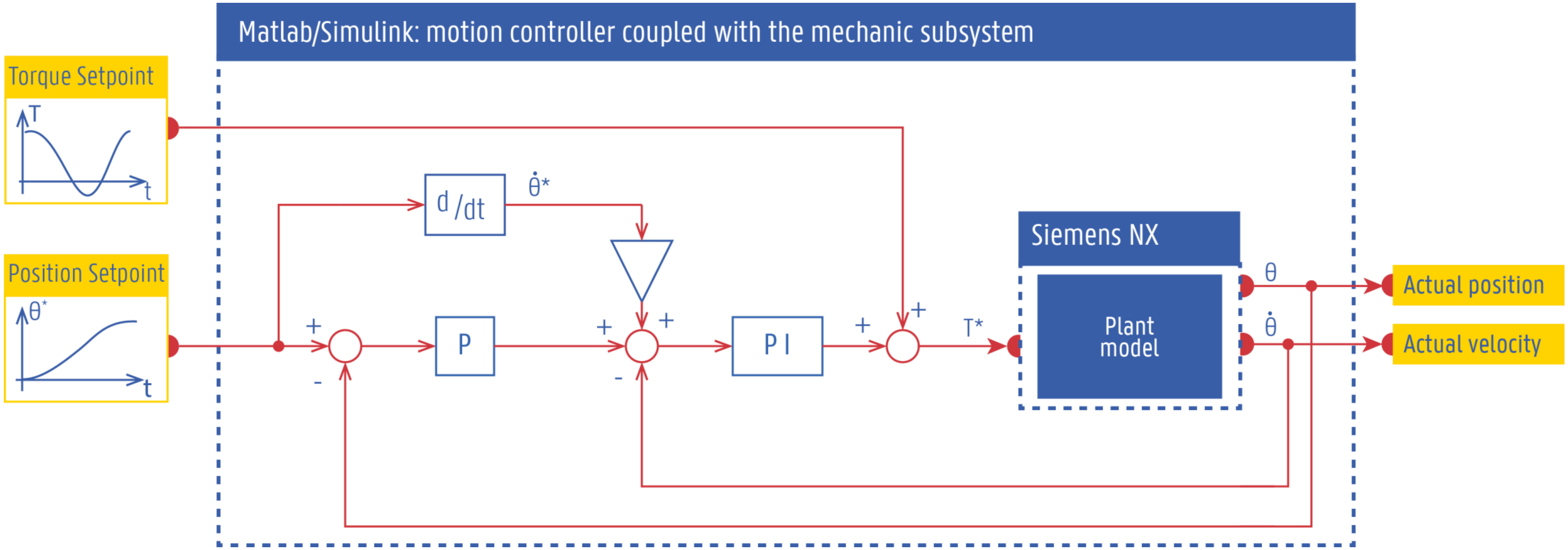


Extraction of data:

- Total reduced inertia
- Total reduced load torque
- Total reduced damping
- Resonance / anti-resonance
- …

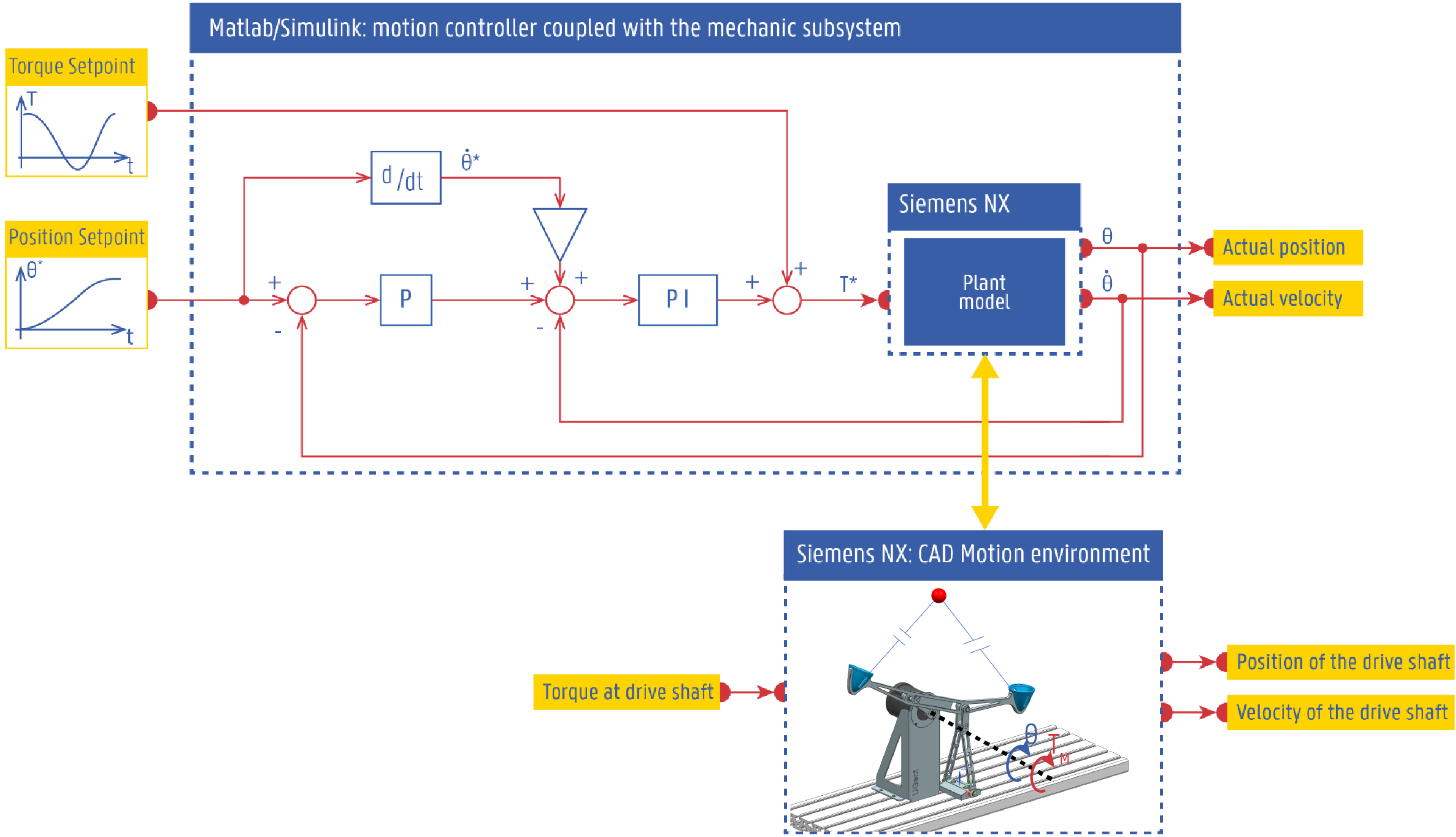
GLOBAL SIMULATION

- The mechanic process is modelled in Siemens NX
- The motion controller is modelled in Matlab/Simulink
- After modelling the subsystems, global simulation is possible, opening the opportunity to:
  - Tune the controller settings
  - Observe the influence of different position setpoints
  - Observe the influence of activating different feedforward-structures



GLOBAL SIMULATION

- Crucial step is to fit the plant model of the process to reality



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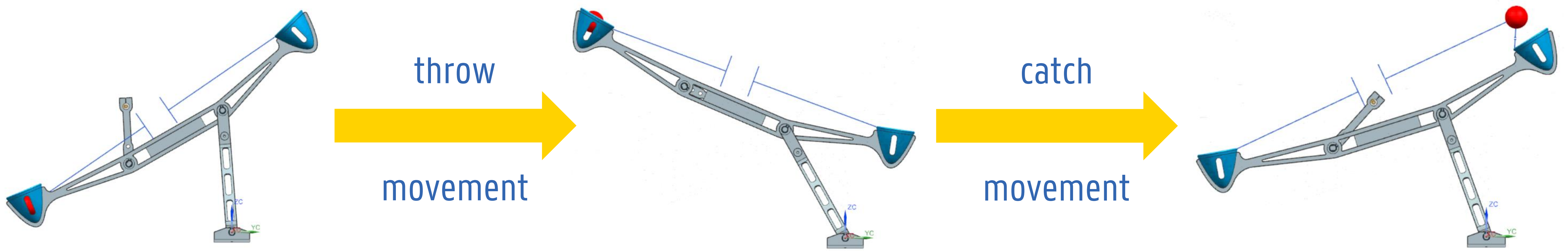
CHALLENGES AND REQUIREMENTS

CHALLENGES AND REQUIREMENTS

- The trajectory cycle can be divided in two parts
- Throw requirement
  - Finding the throw parameters
  - Selection of motor
- Movement to catch position
  - Point-to-point movement in specific time with variable inertia
  - Trajectory optimization



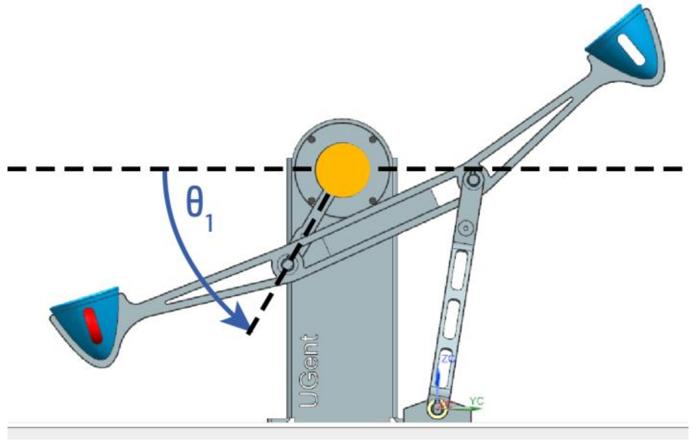
DETERMINATION OF DESIGN PARAMETERS

THE BALL JUGGLER

- The different parameters for a throw cycle

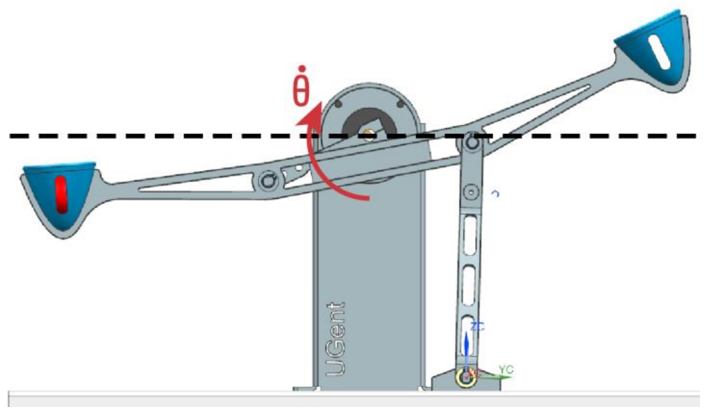
1) Move to start position

→ Start angle θ_1



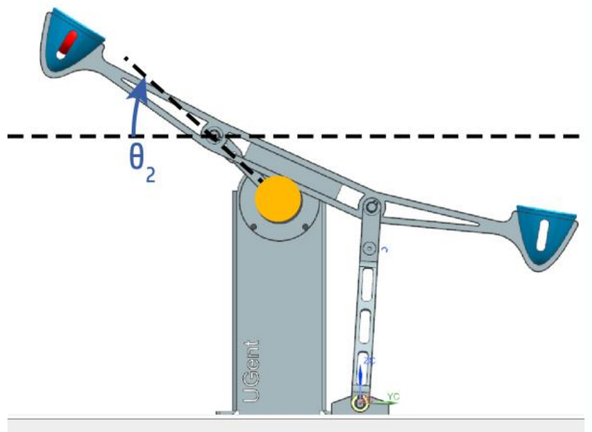
2) Constant speed at driver

→ Throw speed $\dot{\theta}$

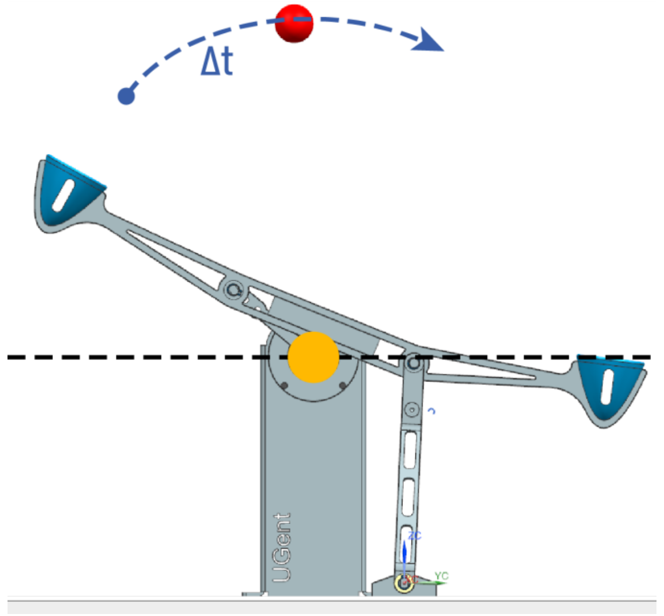


3) constant speed until throw position reached

→ Throw angle θ_2

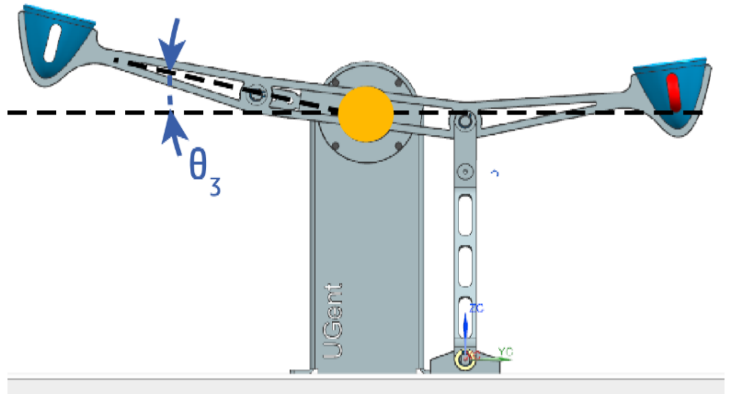


Throw time Δt



4) Move to catch position

→ Catch angle θ_3



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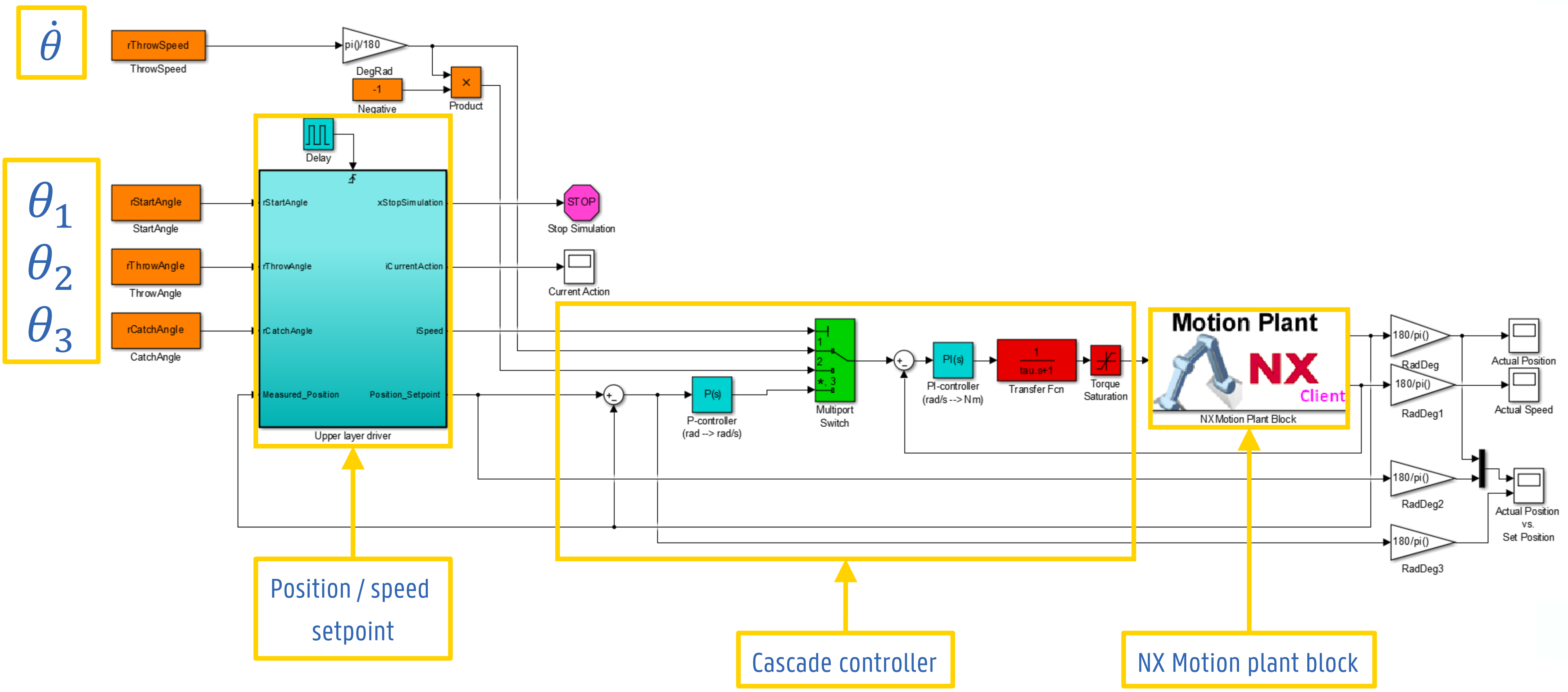
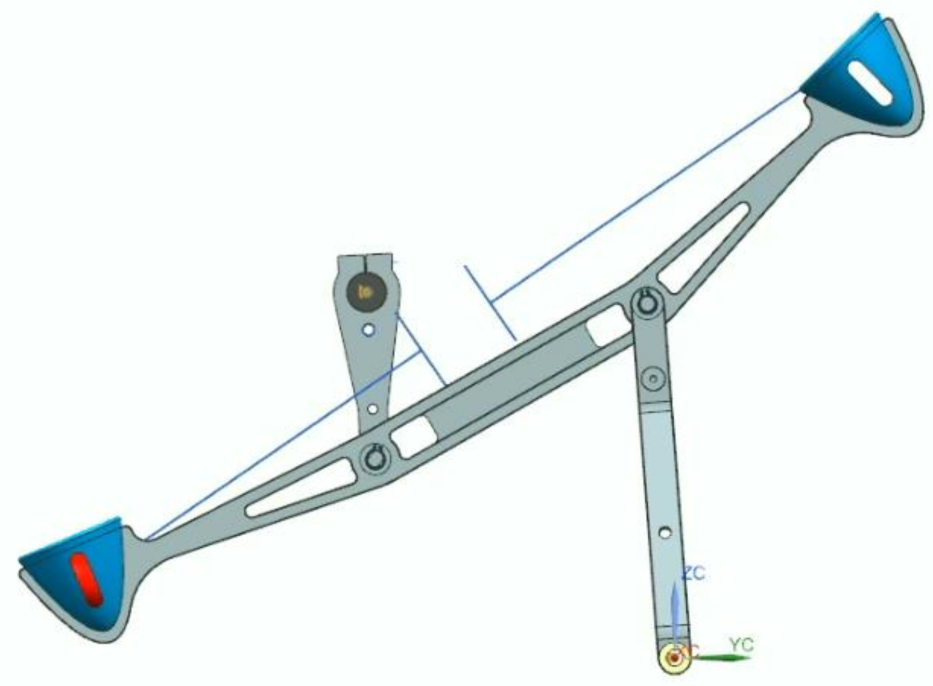
THE BALL JUGGLER

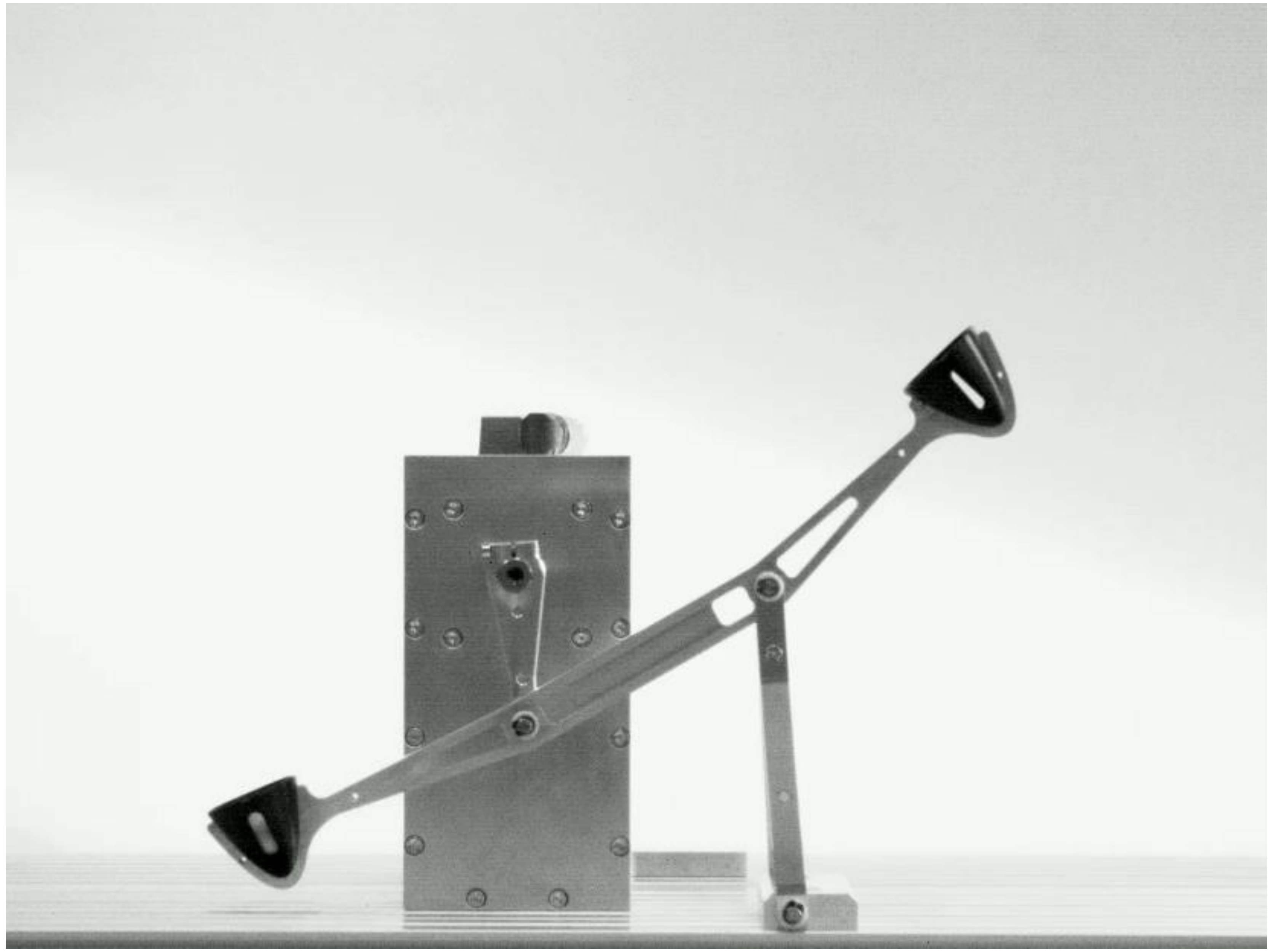
- With co-simulations, the parameters can easily be determined





THE BALL JUGGLER

- Validation of the virtual throw parameters



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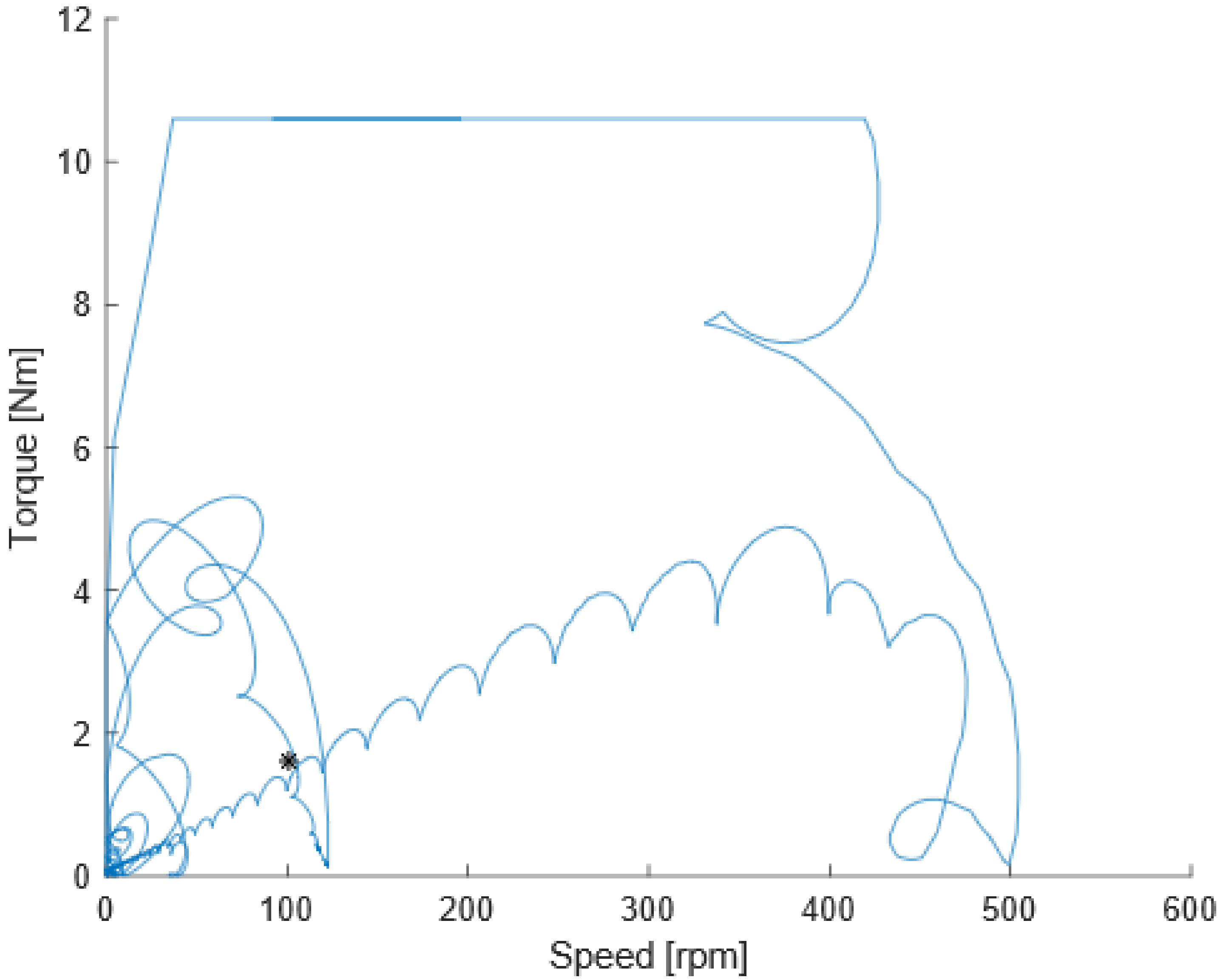
MOTOR SELECTION

MOTOR SELECTION

- Throw requirement
  - Start angle: -3°
  - Throw speed: 736°/s
  - Throw angle: 128°
  - Catch angle: 42°
- Torque-speed curve
  - Input for motor selection



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  - Catch angle: 42°
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1FK7042-5AK71-1UG0

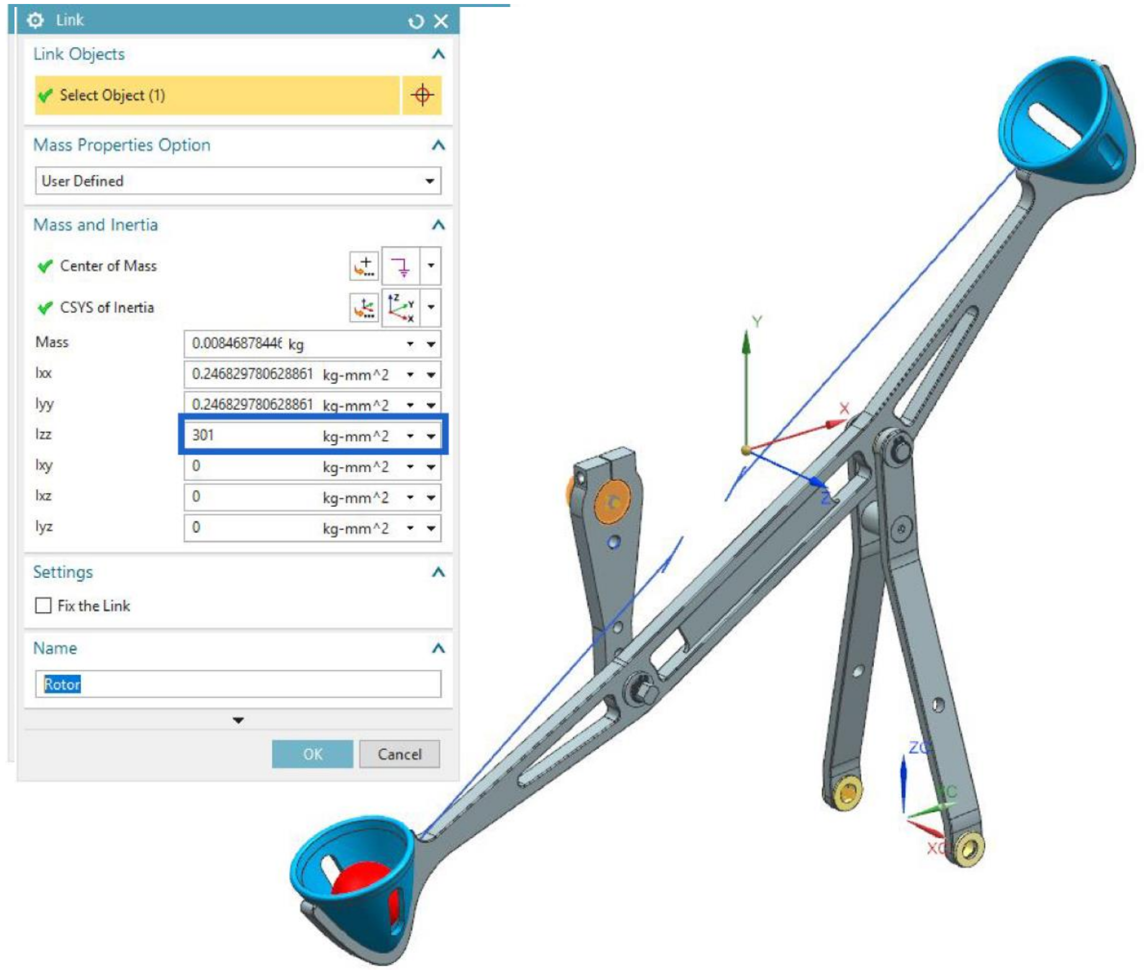
Engineering data	
Rated speed (100 K)	6000 rpm
Number of poles	8
Rated torque (100 K)	1.5 Nm
Rated current	2.5 A
Static torque (60 K)	2.50 Nm
Static torque (100 K)	3.0 Nm
Stall current (60 K)	3.6 A
Stall current (100 K)	4.4 A
Moment of inertia	3.010 kgcm²
Efficiency	89.0 %

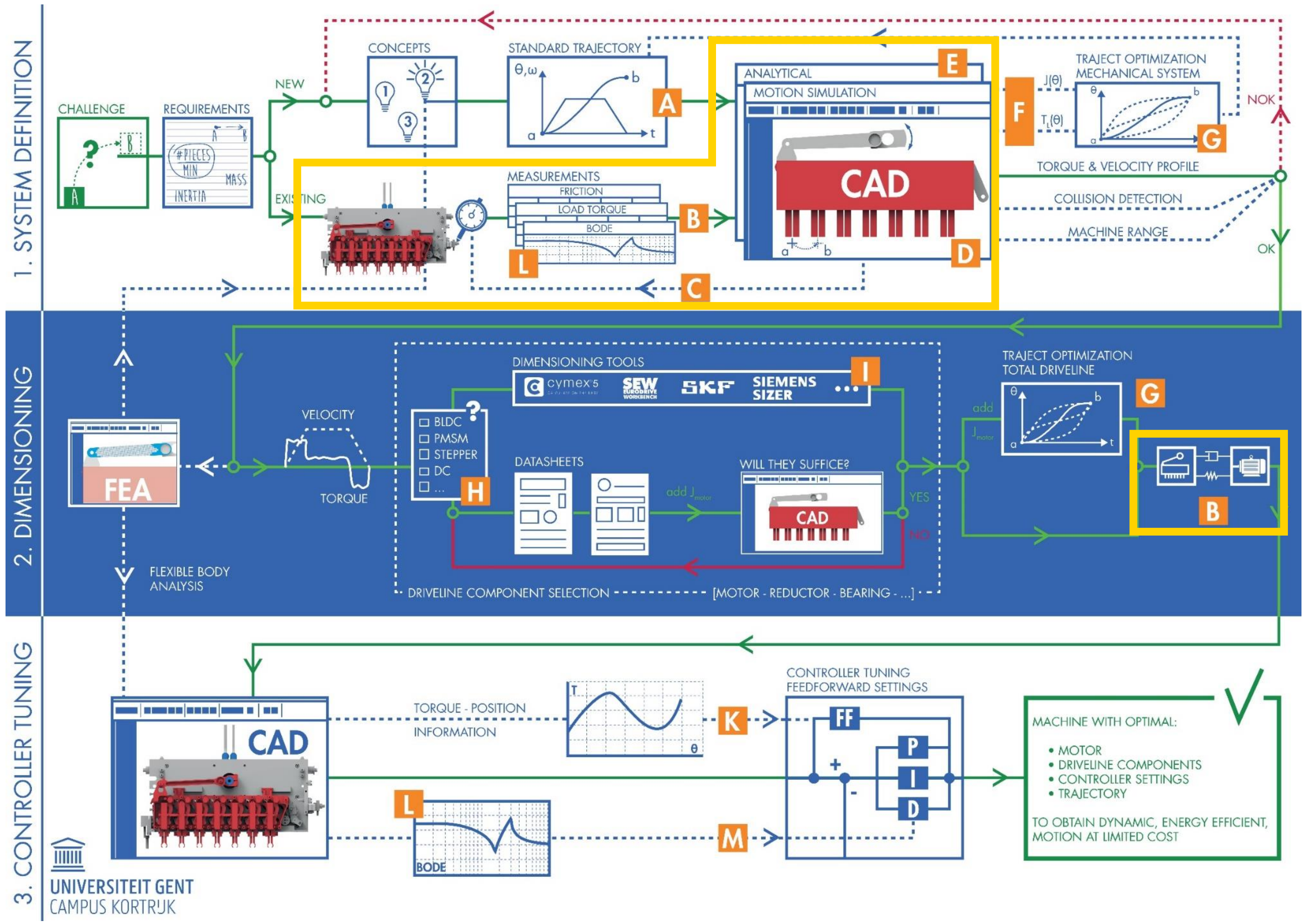
Physical constants	
Torque constant	0.69 Nm/A
Voltage constant at 20° C	44.0 V/1000*min⁻¹
Winding resistance at 20° C	1.20 Ω
Rotating field inductance	6.7 mH
Electrical time constant	5.60 ms
Mechanical time constant	2.27 ms
Thermal time constant	30 min
Shaft torsional stiffness	16000 Nm/rad
Net weight of the motor	4.9 kg

Mechanical data	
Motor type	Permanent-magnet synchronous motor
Motor type	Compact
Shaft height	48
Cooling	Natural cooling
Radial runout tolerance	0.040 mm
Concentricity tolerance	0.08 mm
Axial runout tolerance	0.08 mm
Vibration severity grade	Grade A
Connector size	1
Degree of protection	IP64
Design acc. to Code I	IM B5 (IM V1, IM V3)
Temperature monitoring	KTY84 temperature sensor in the stator winding
Electrical connectors	Connectors for signals and power rotatable
Color of the housing	without
Holding brake	without holding brake
Shaft extension	Plain shaft
Encoder system	Resolver R15DQ: resolver 15 bits (resolution 32768, internal multi-pole)

MOTOR SELECTION

- Adding flexibility, damping and rotor inertia
  - Flexible coupling: based on previous knowledge
    - $k = 490$ Nm/rad , $b = 0{,}04$ Nms/rad
  - Rotor inertia: data-sheet of the selected motor
    - $J = 0{,}000301$ kgm²





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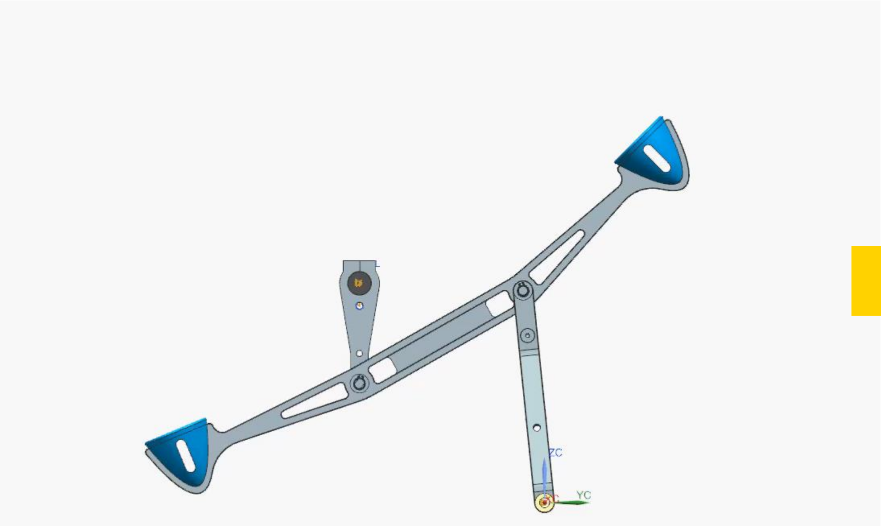
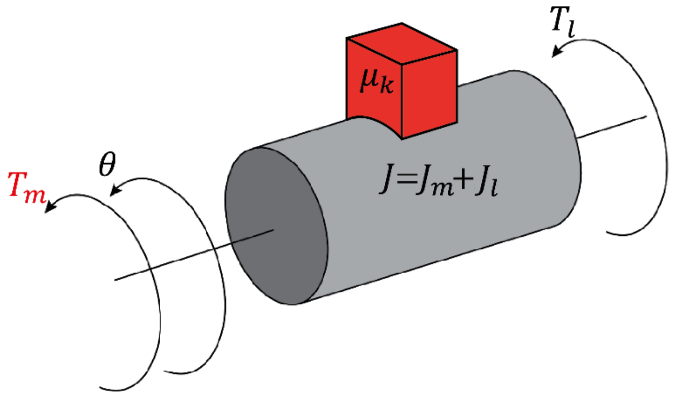
OPTIMIZATION AND TUNING

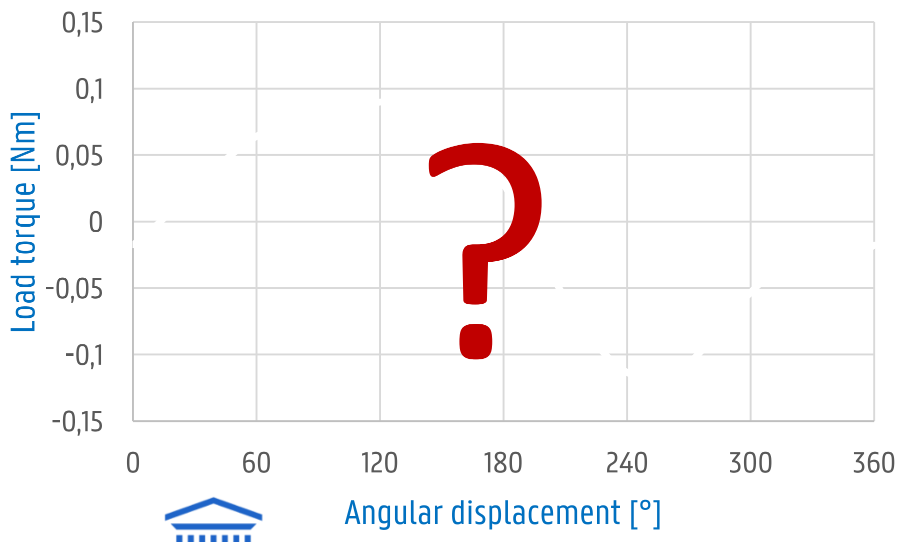
OPTIMIZATION AND TUNING

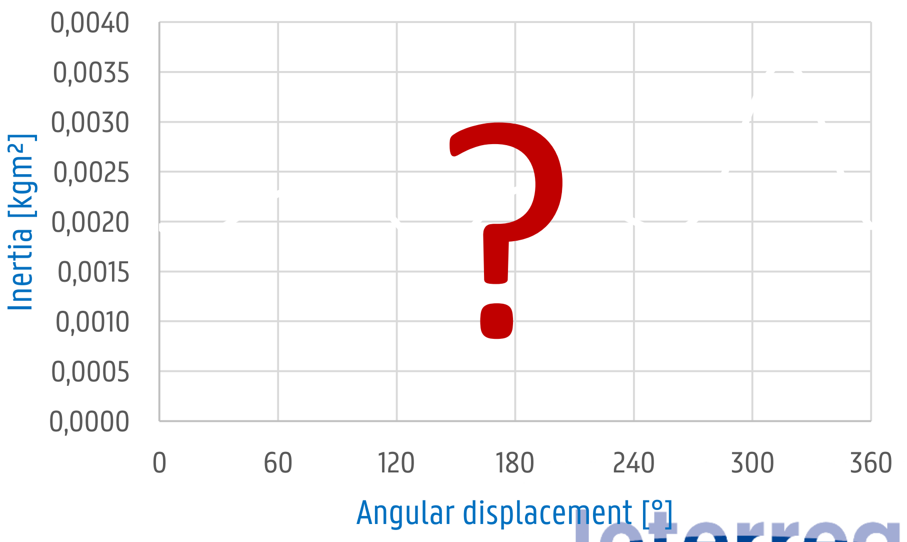
- Extracting total reduced inertia and load torque
  - Important information for:
    - Finding an optimized trajectory
    - Controller tuning (based on bode on highest inertia)

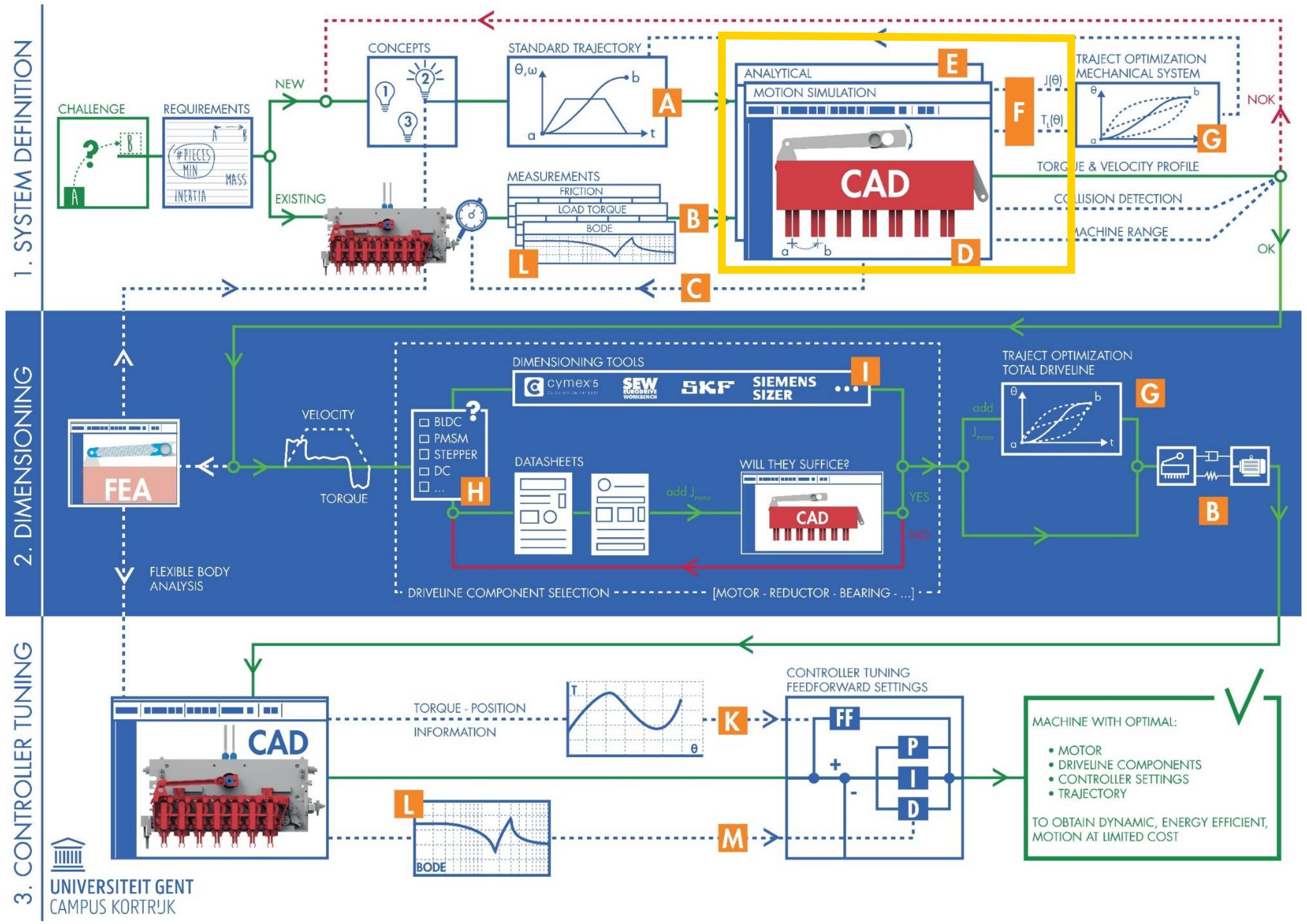


$$T_m = T_l + \mu_k \dot{\theta} + \frac{1}{2}\frac{dJ}{d\theta}(\dot{\theta})^2 + J\ddot{\theta}$$









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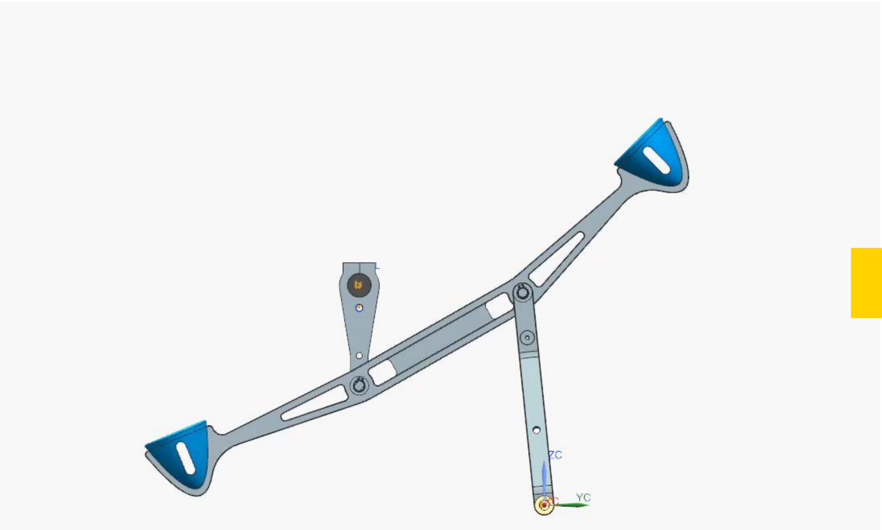
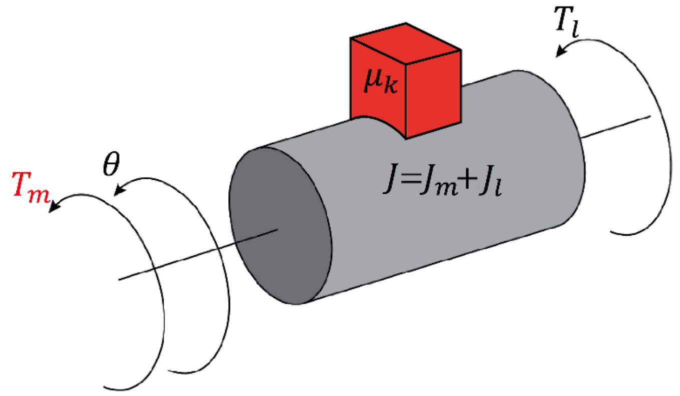
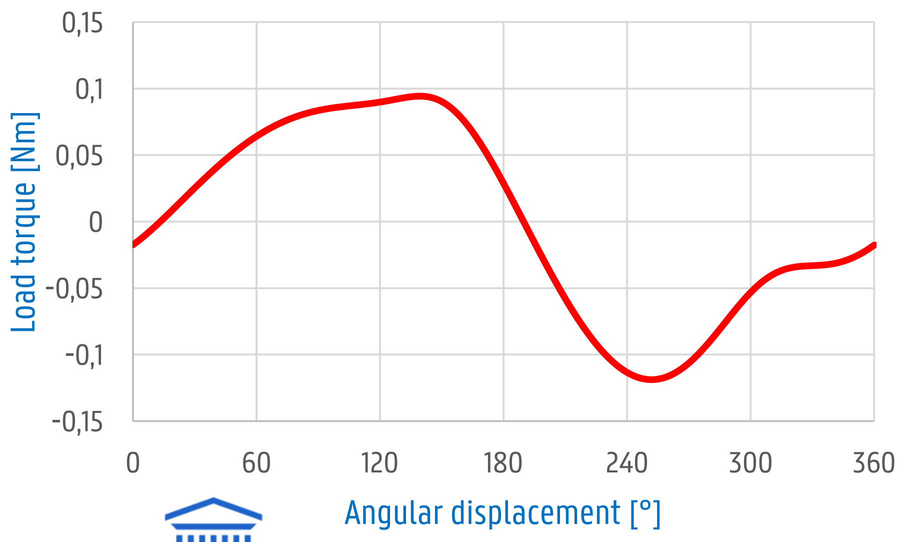
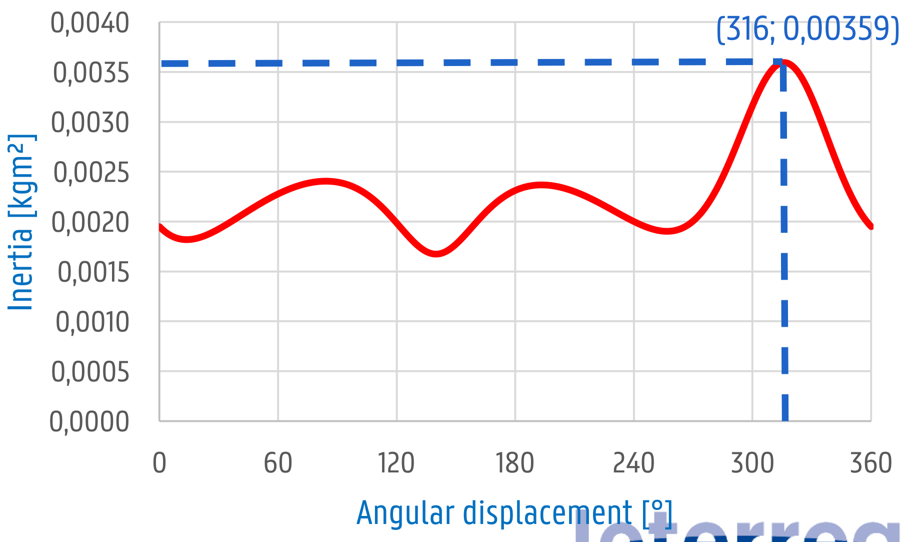
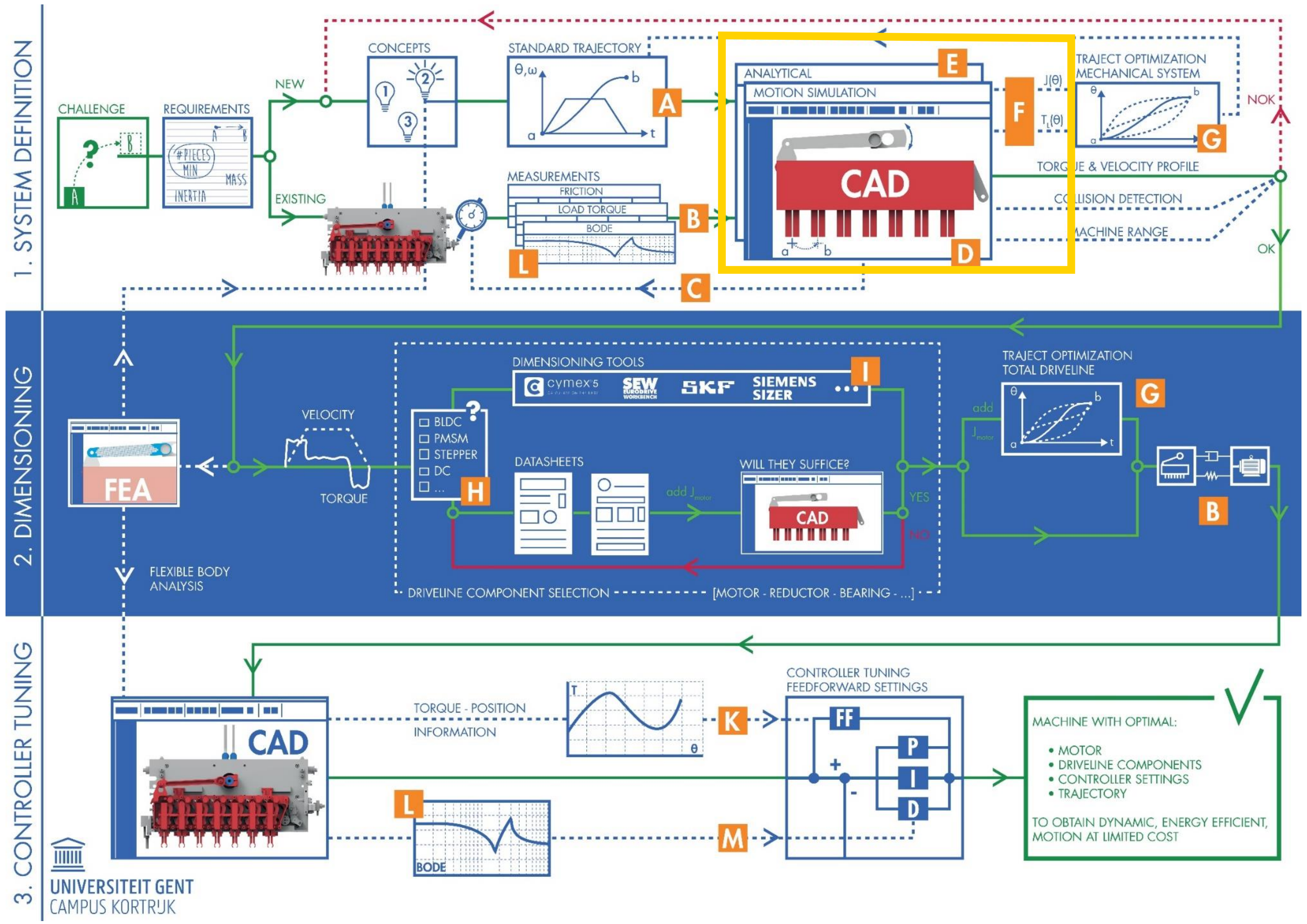


$$T_m = T_l + \mu_k \dot{\theta} + \frac{1}{2}\frac{dJ}{d\theta}\left(\dot{\theta}\right)^2 + J\ddot{\theta}$$



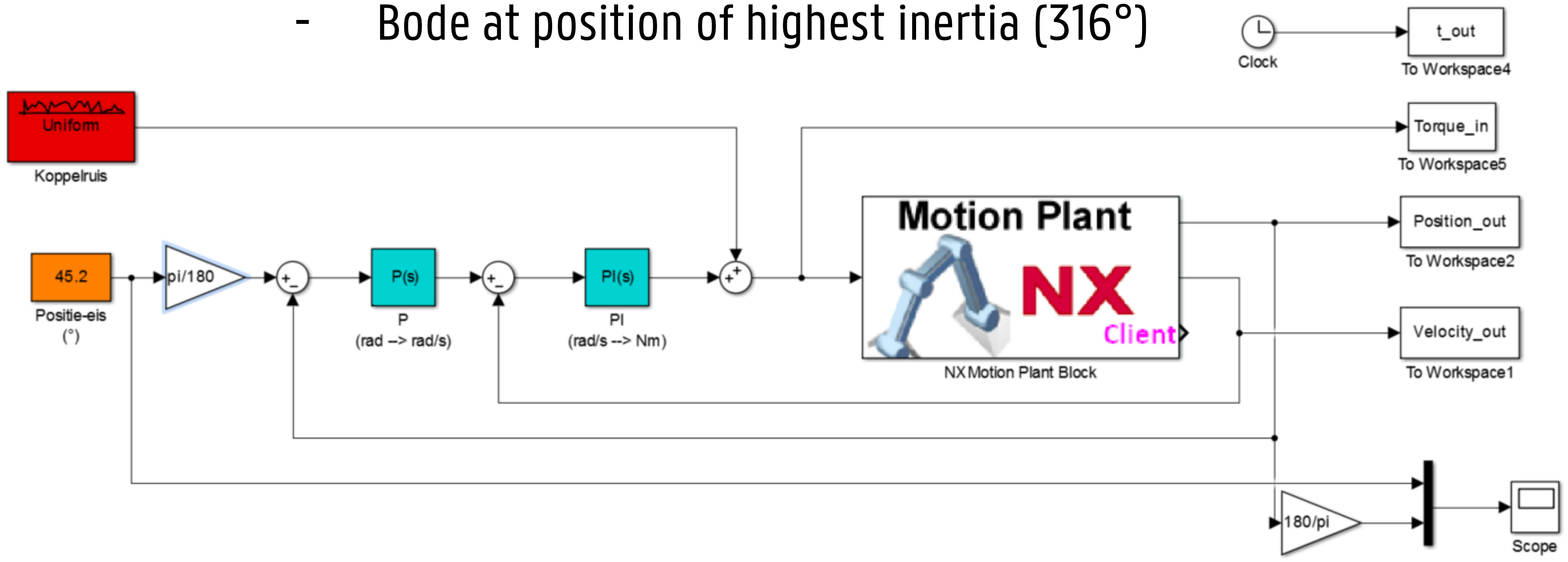


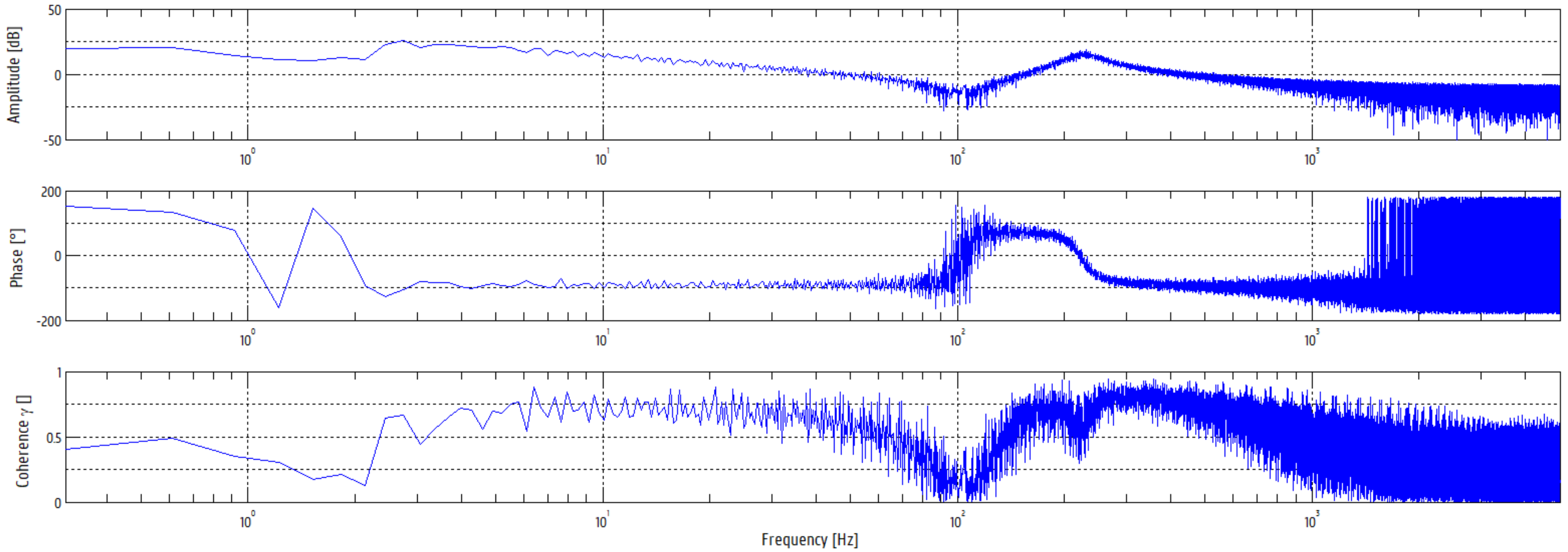


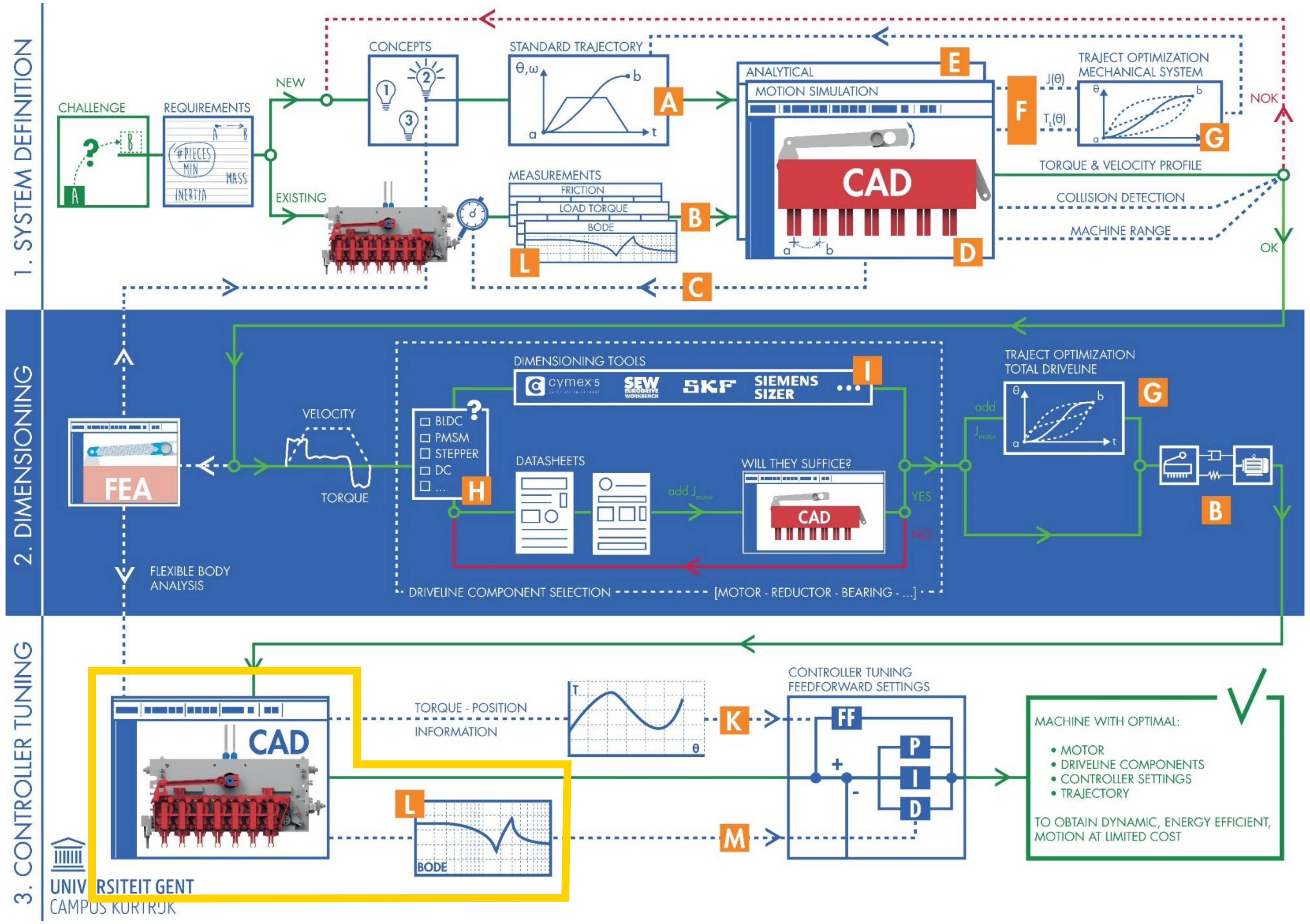


OPTIMIZATION AND TUNING

- Controller tuning
  - Bode at position of highest inertia (316°)







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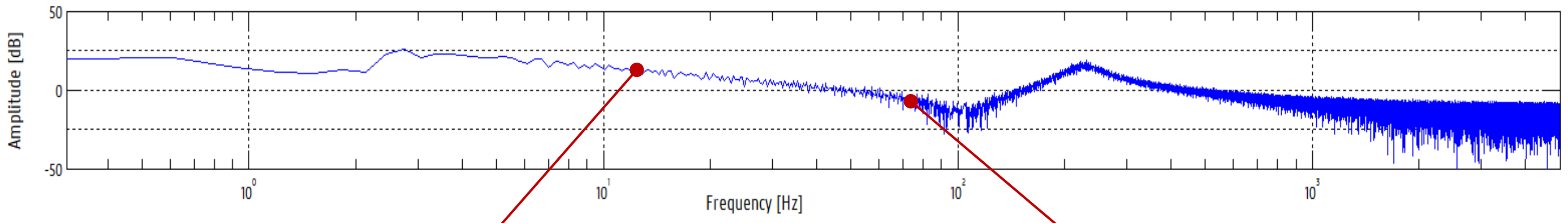
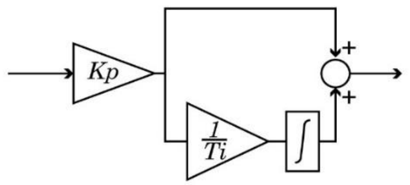
OPTIMIZATION AND TUNING

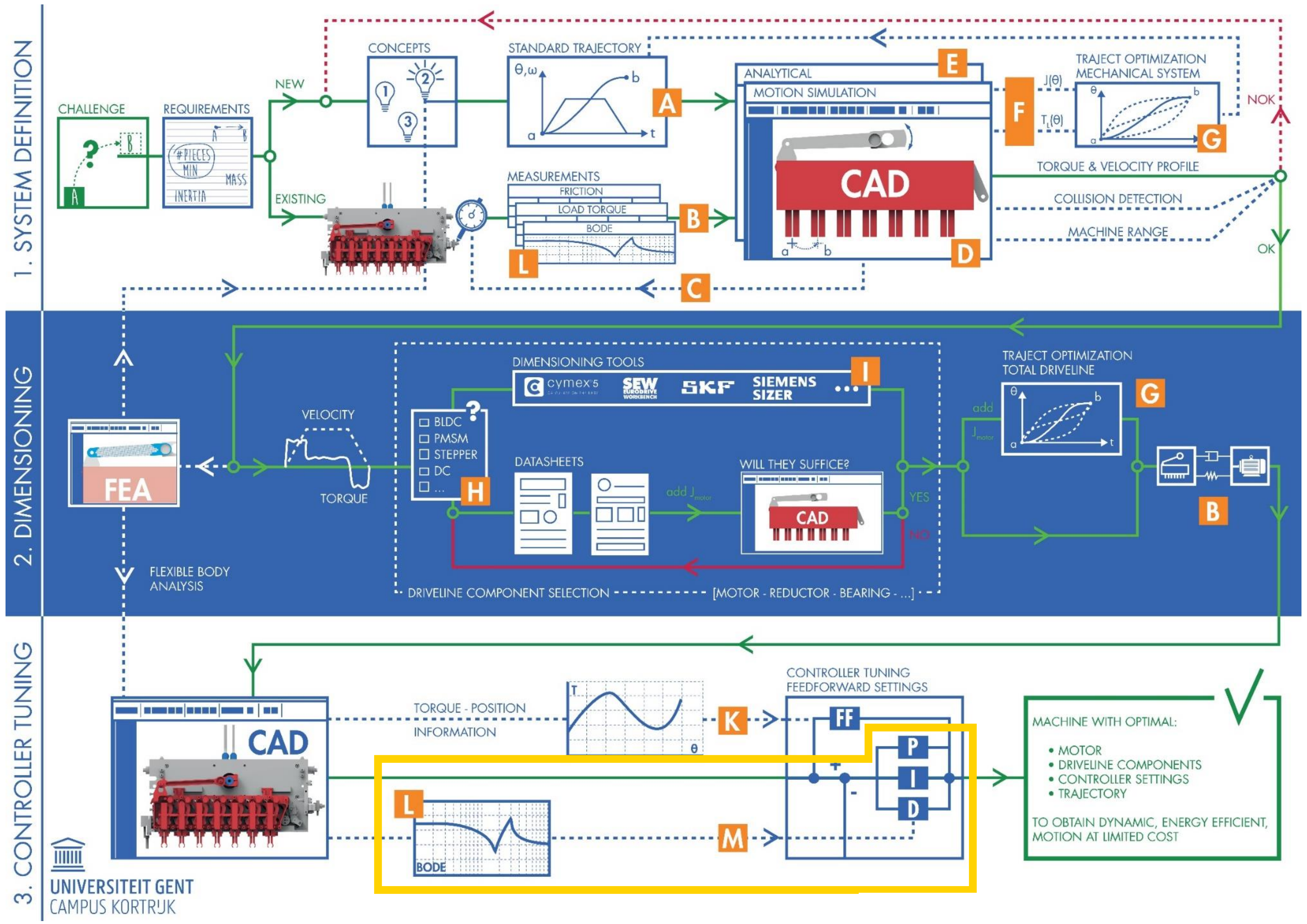
- Controller tuning
  - Determination of PI-settings of the speed controller
  - Both robust and aggressive are considered



Input		
f_{PM}	14	[Hz]
$\|G\|_{f=f_{PM}}$	6	[dB]
Output		
T_i	0,019667004	
K_p	0,434010264	



Input		
f_{PM}	79	[Hz]
$\|G\|_{f=f_{PM}}$	-21	[dB]
Output		
T_i	0,003485292	
K_p	9,716279516	



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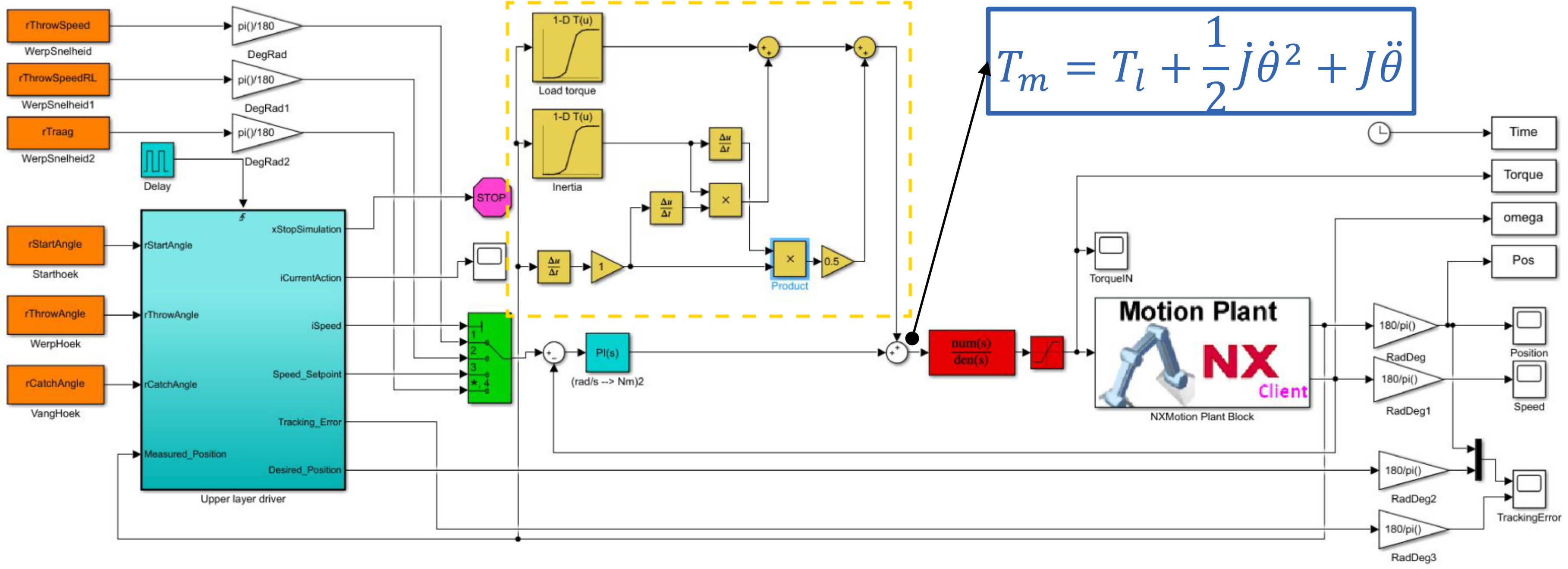
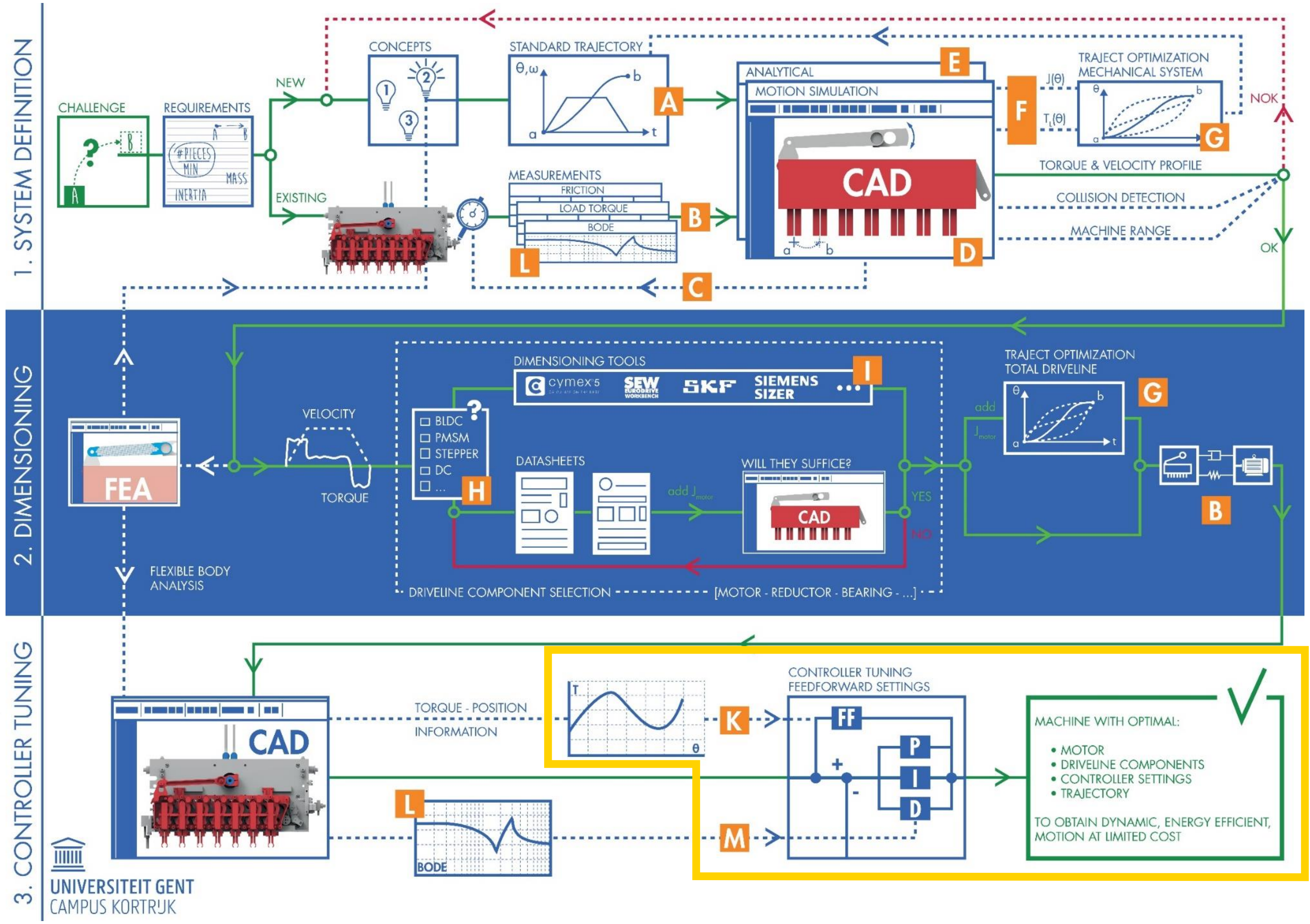
OPTIMIZATION AND TUNING

- Torque feedforward with torque formula
  - Virtual machine

$$T_m = T_l + \frac{1}{2}\dot{J}\dot{\theta}^2 + J\ddot{\theta}$$

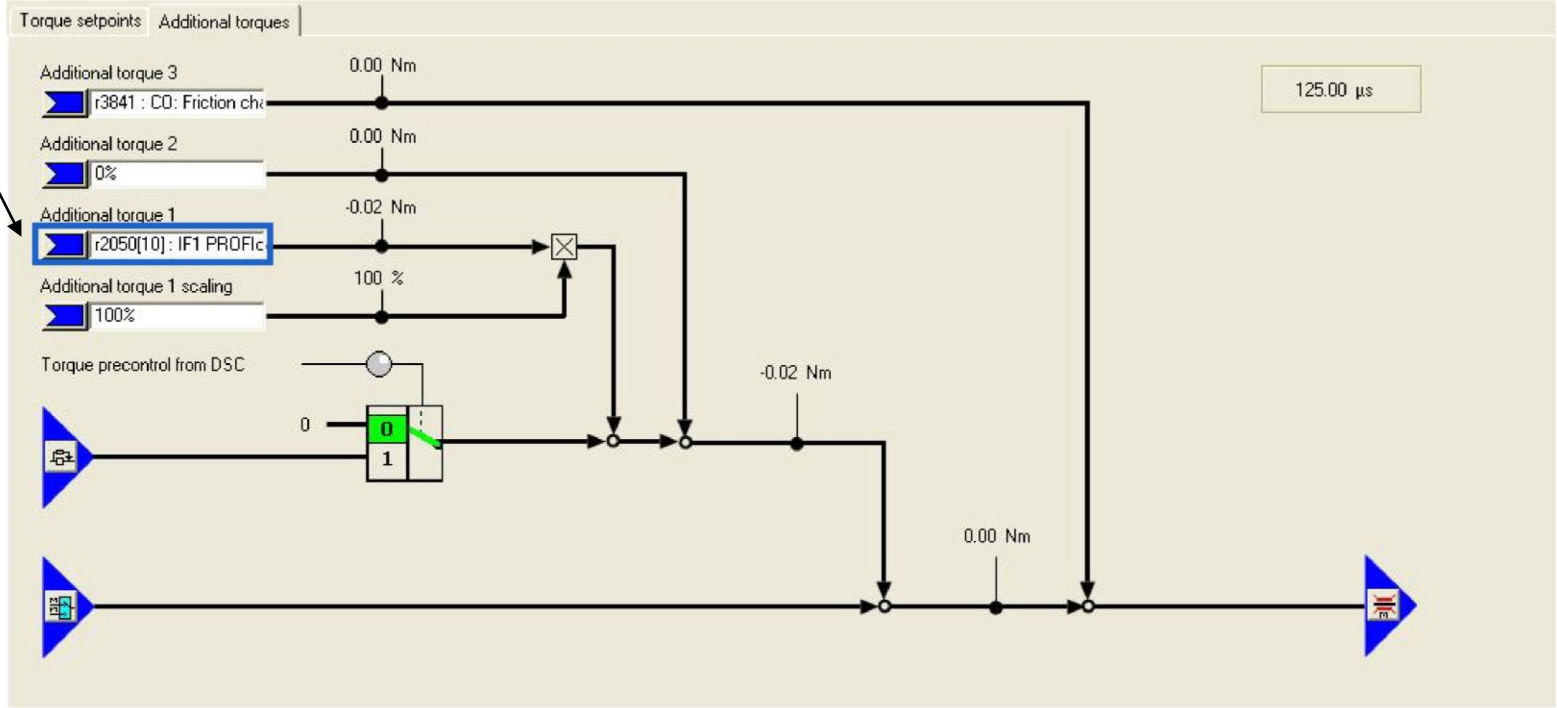


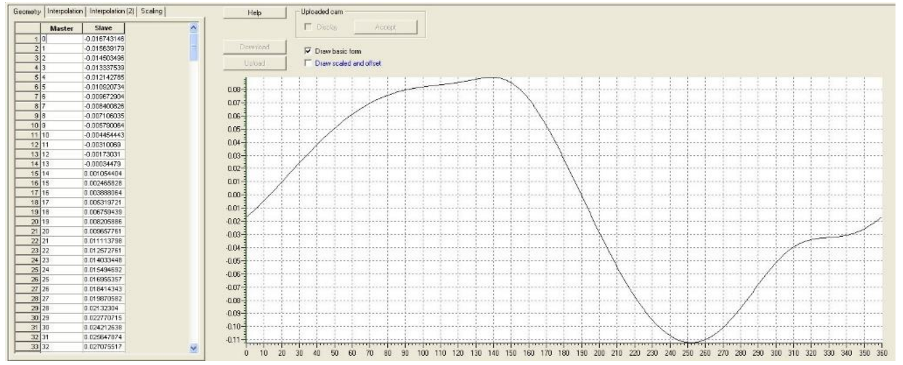


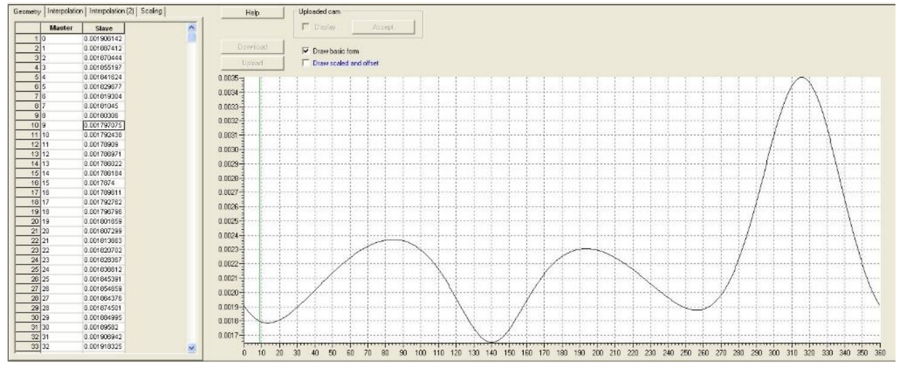
OPTIMIZATION AND TUNING

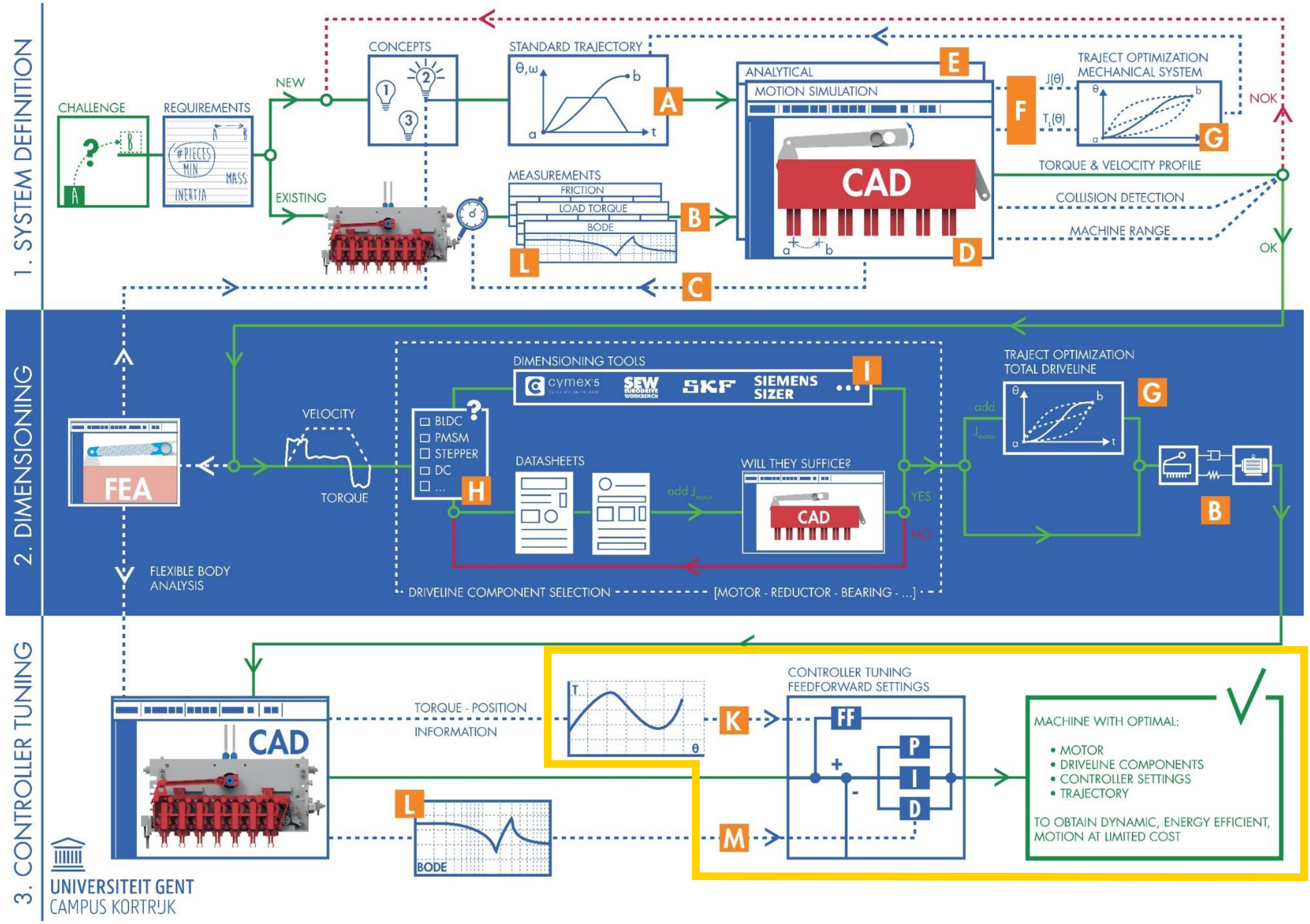
- Torque feedforward with torque formula
  - Real machine

$$T_m = T_l + \frac{1}{2}\dot{J}\dot{\theta}^2 + J\ddot{\theta}$$









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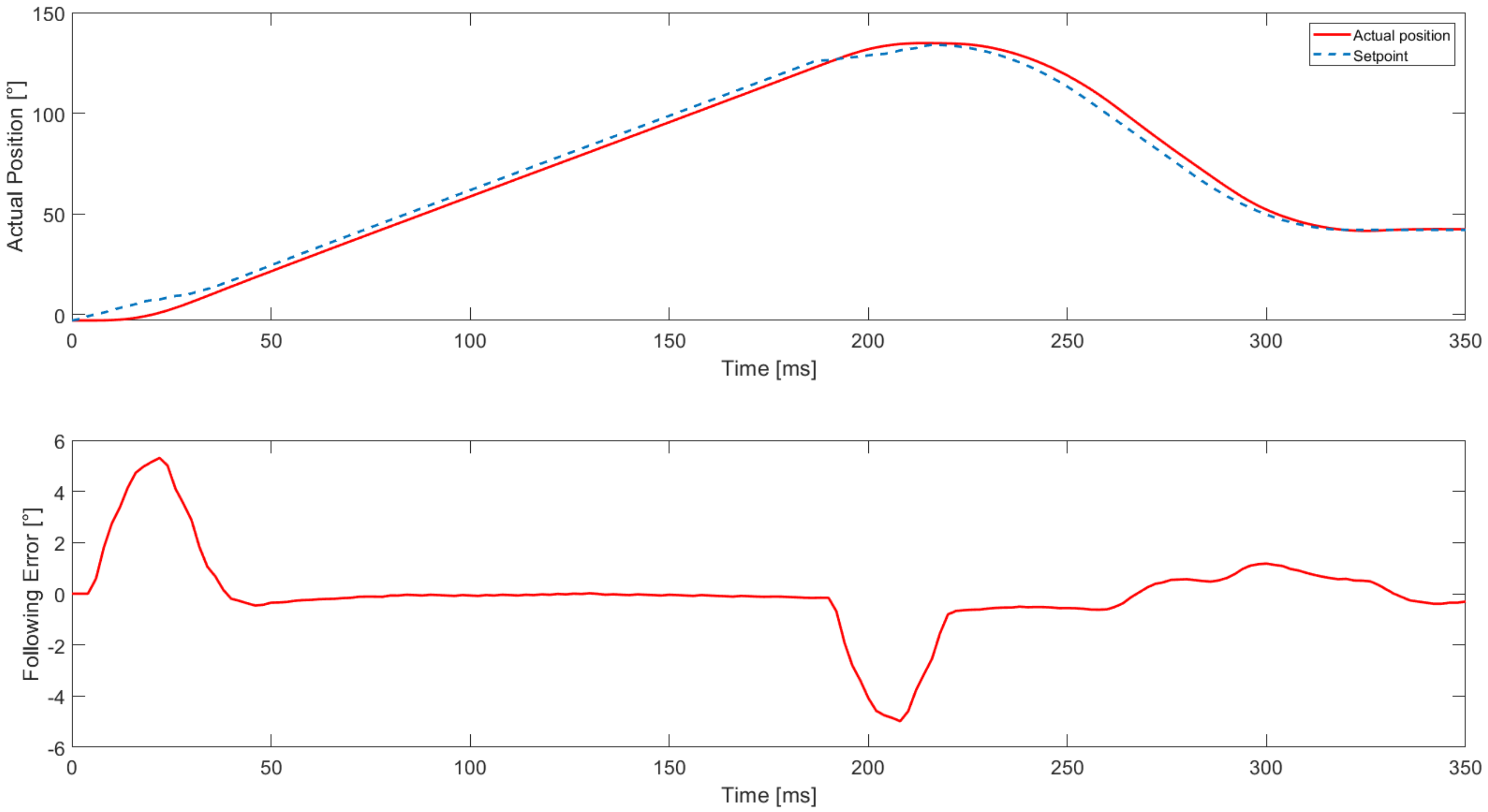
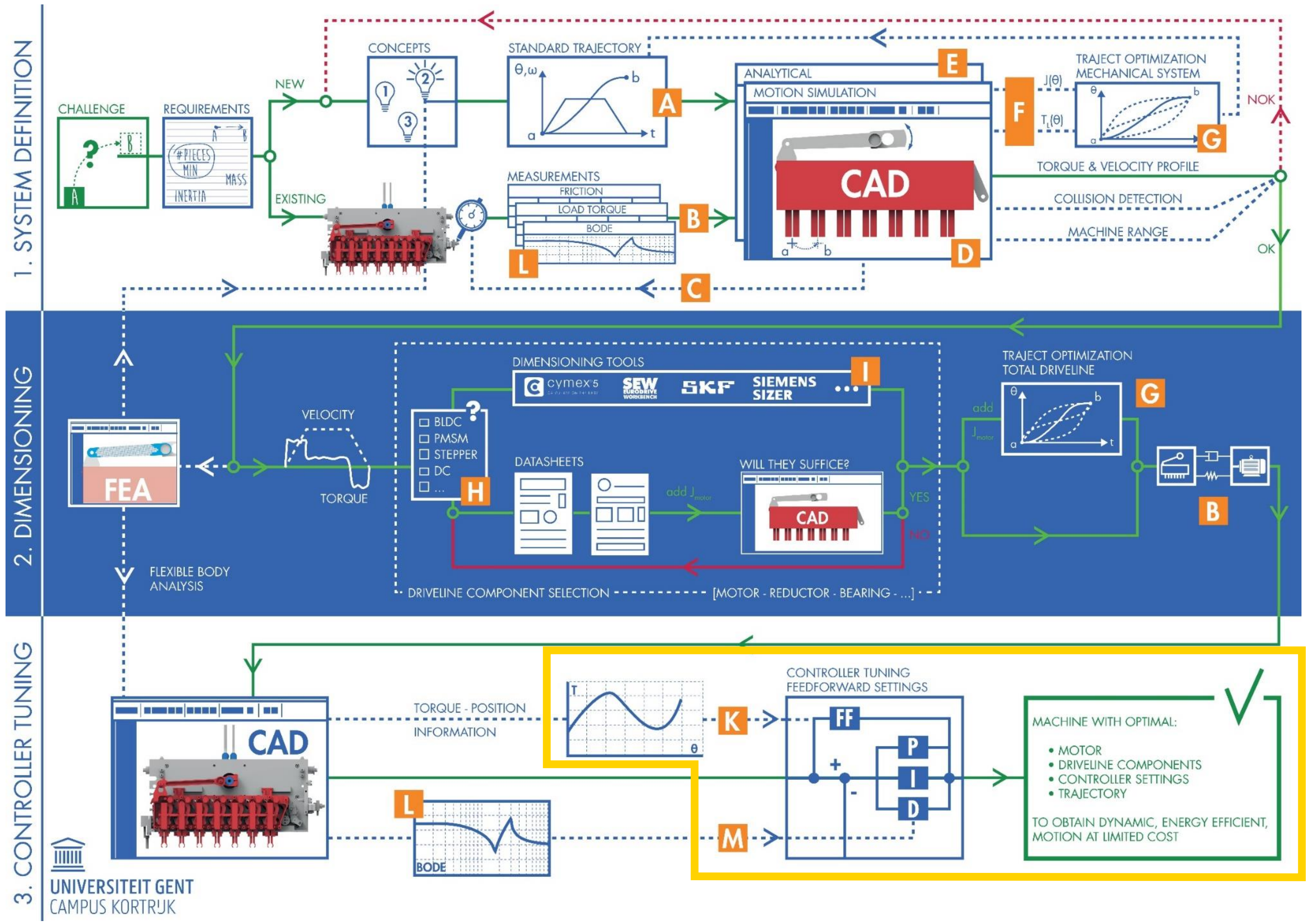
OPTIMIZATION AND TUNING

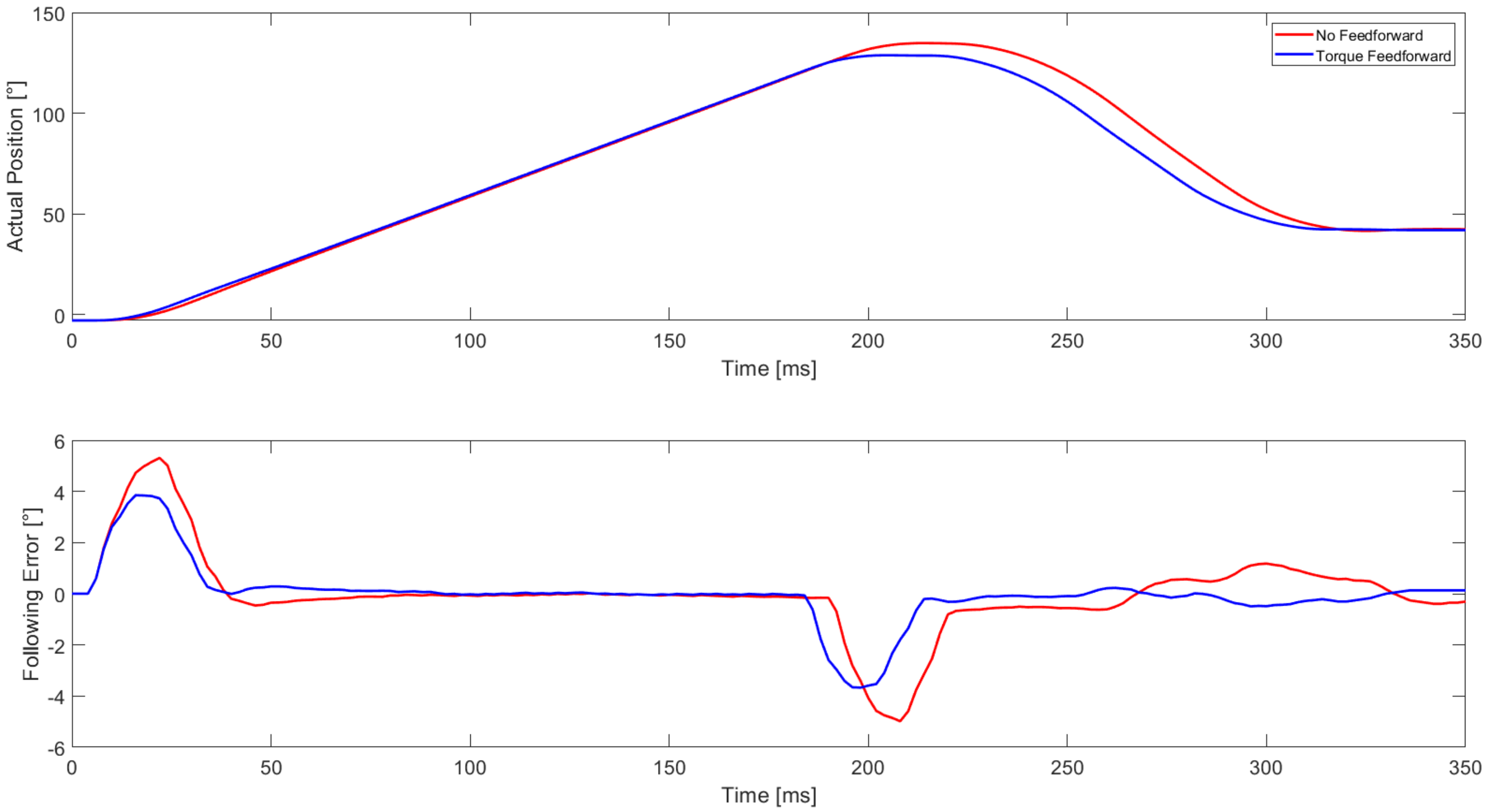
- Movement of the ball juggler:
  - Position – tracking error

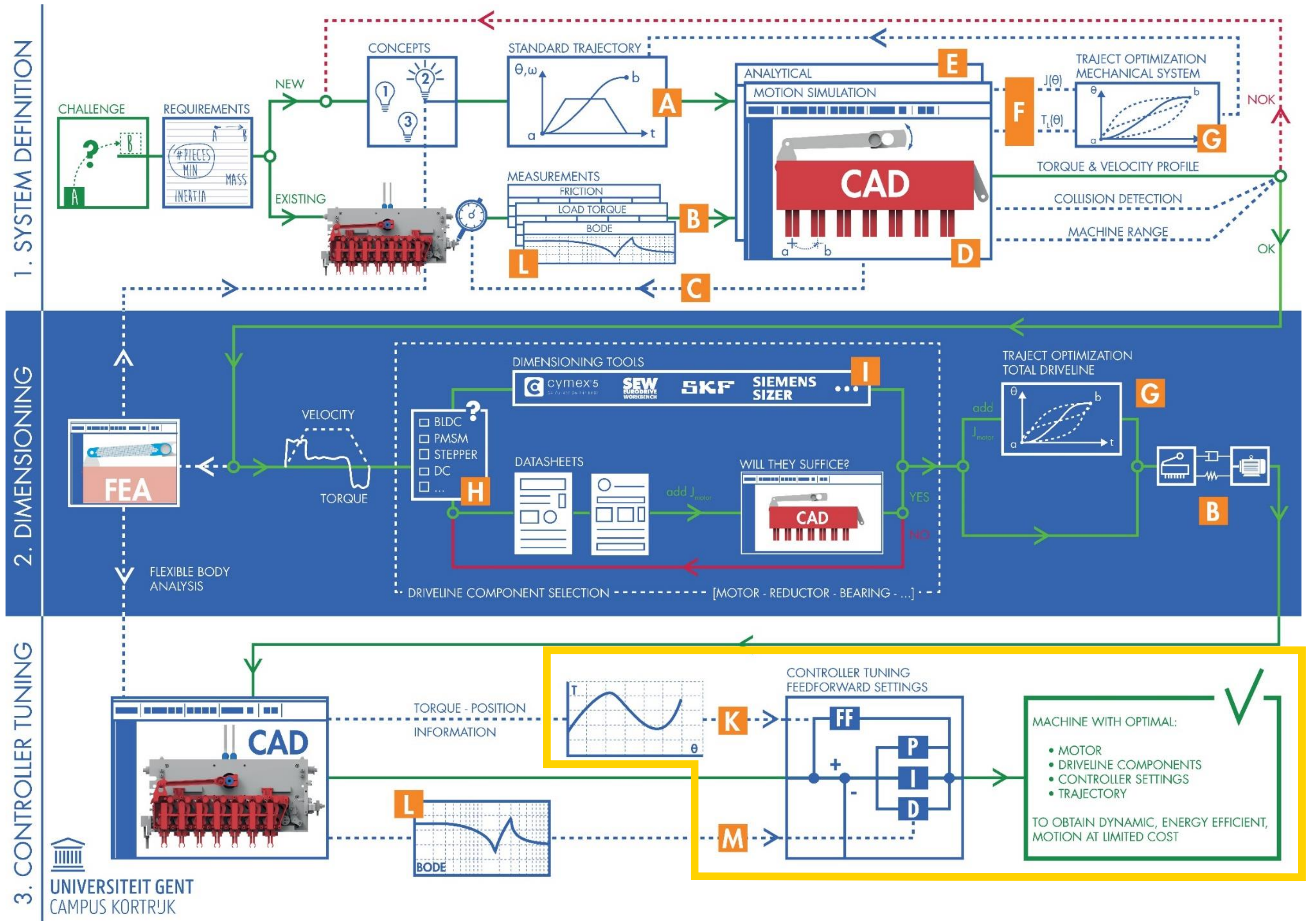




OPTIMIZATION AND TUNING

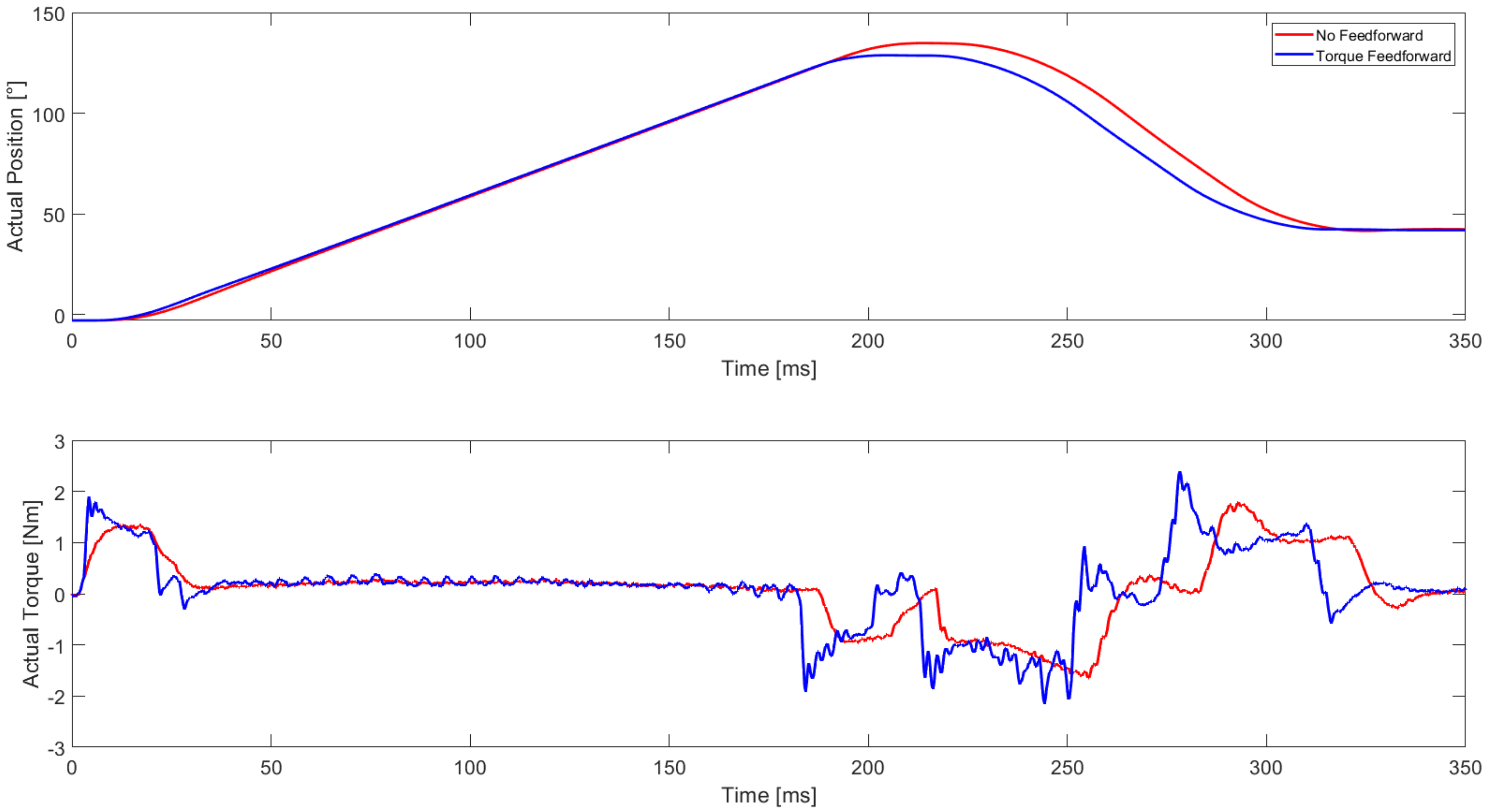
- Torque feedforward:
  - Position – tracking error

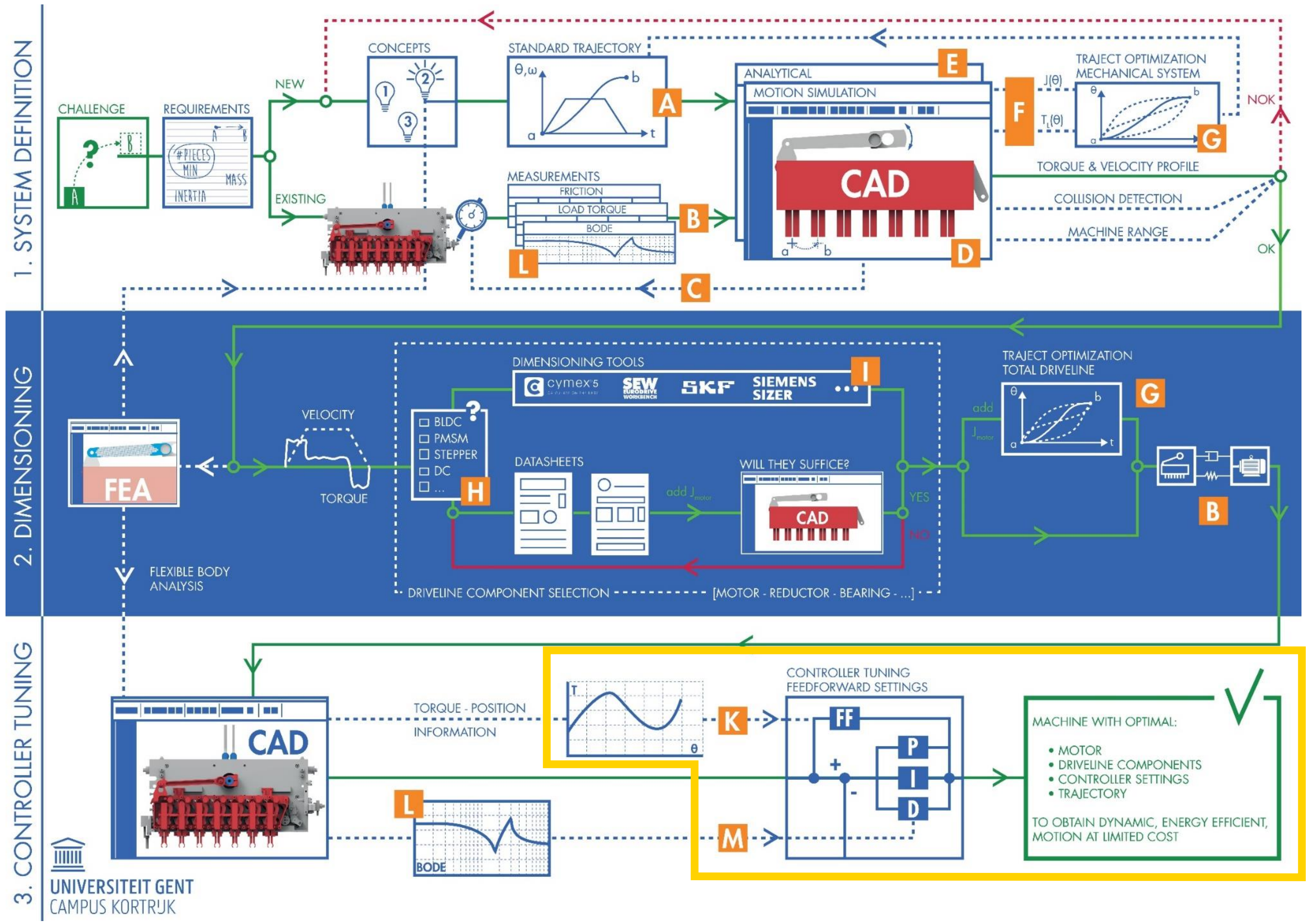




OPTIMIZATION AND TUNING

- Torque feedforward:
  - Position – torque





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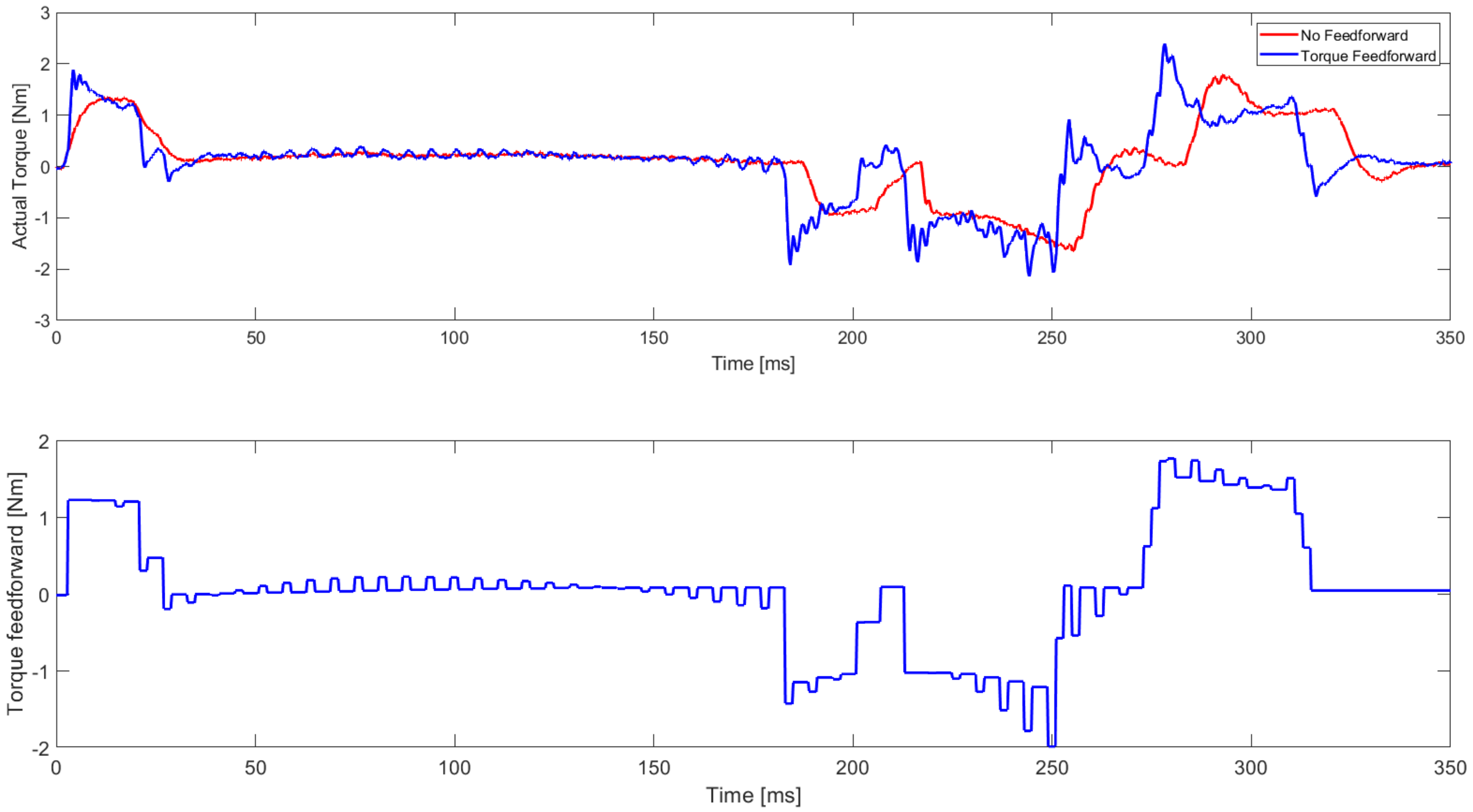
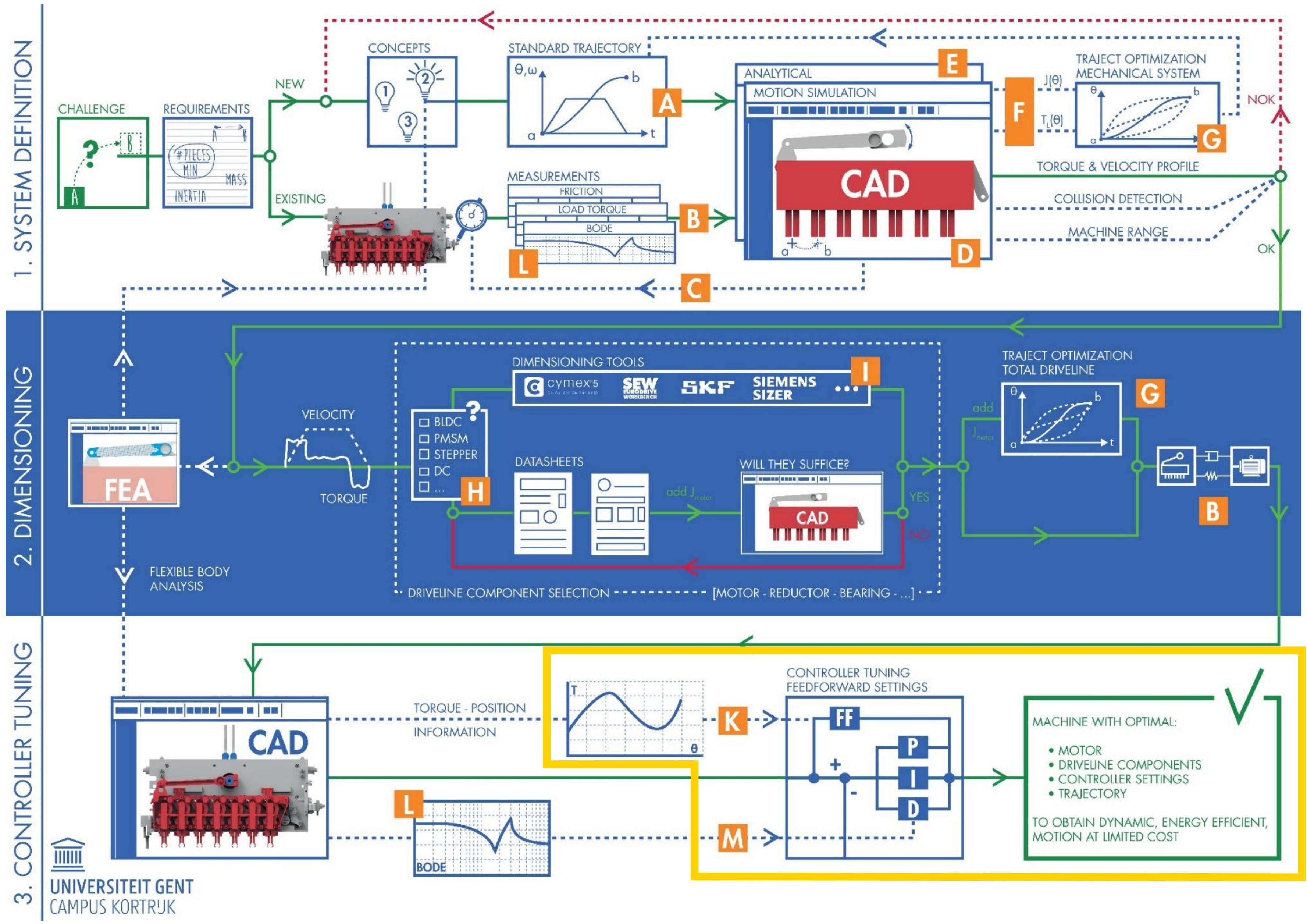
OPTIMIZATION AND TUNING

- Torque feedforward:
  - Torque – torque feedforward





CONCLUSION

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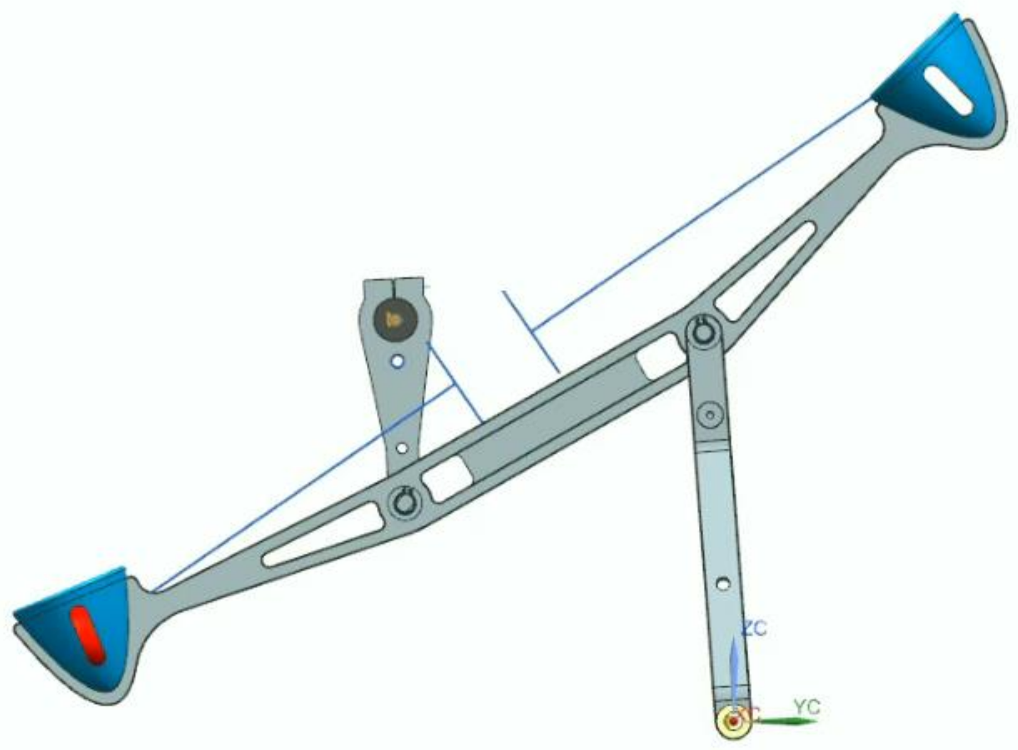
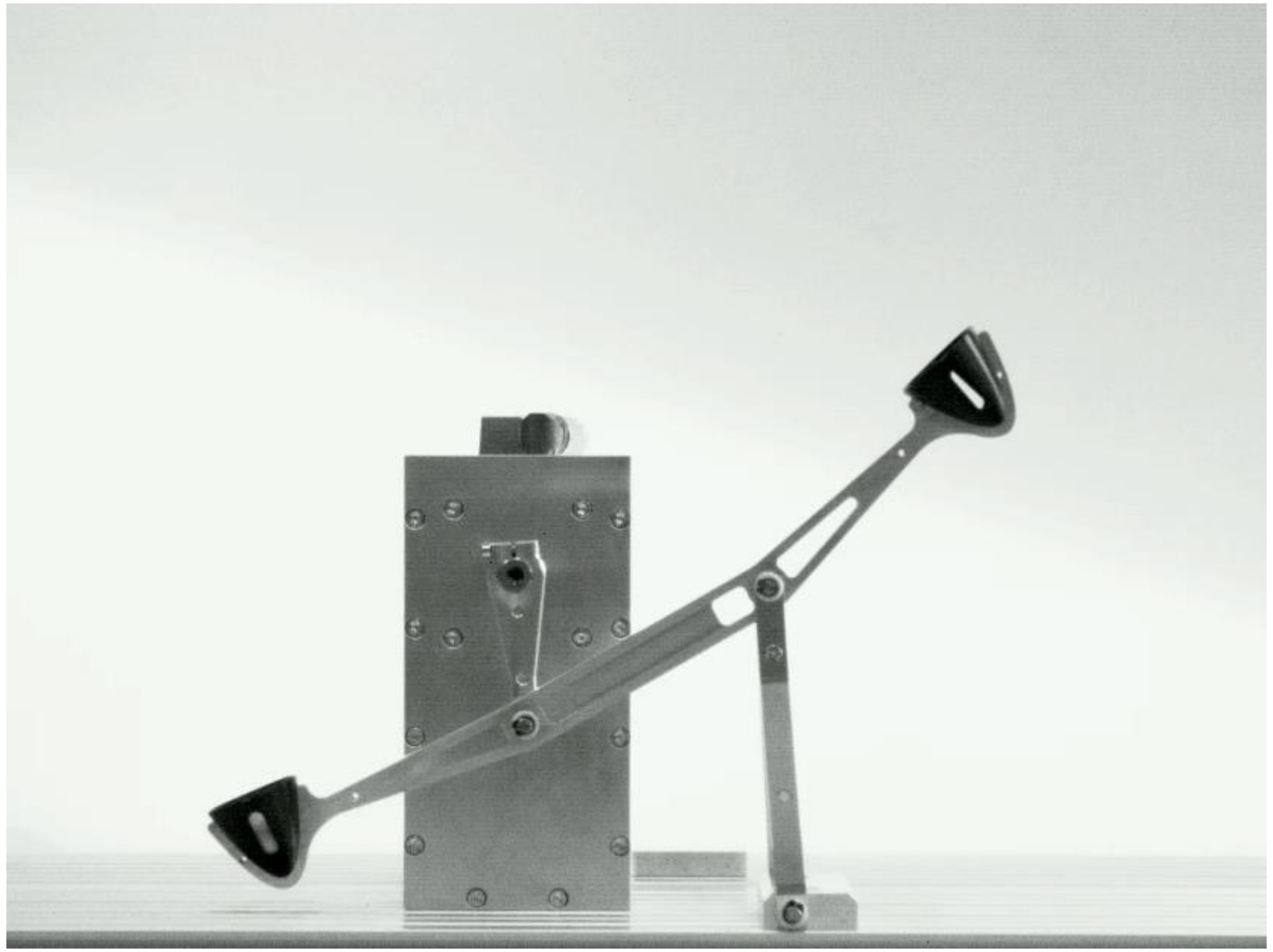
- Virtual design and optimization of a mechatronic system
- Implementation of virtual optimizations on the real machine
- Future works:
    - Trajectory optimization for catch movement
    - Validate workflow with drives of other manufacturers





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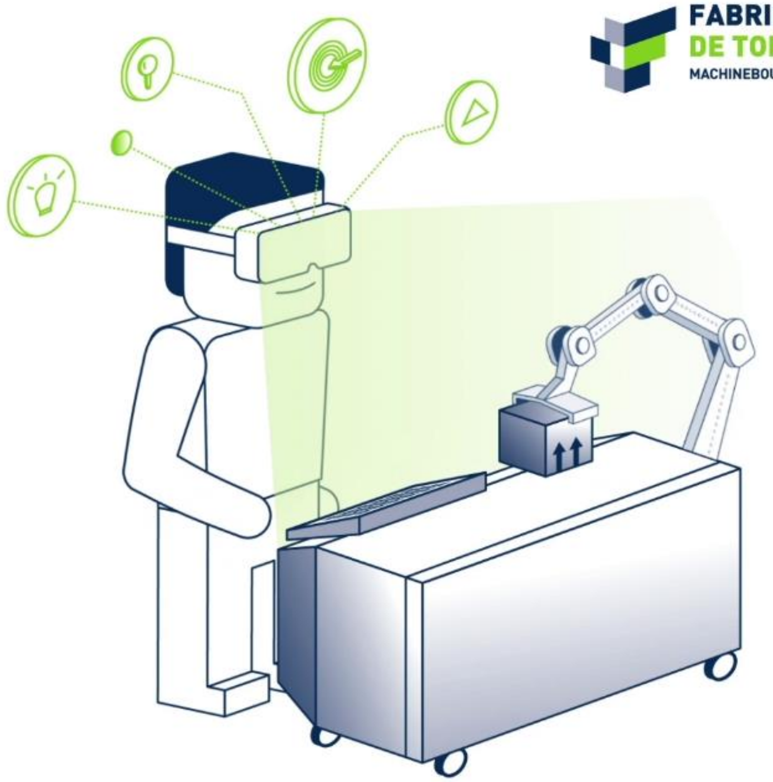
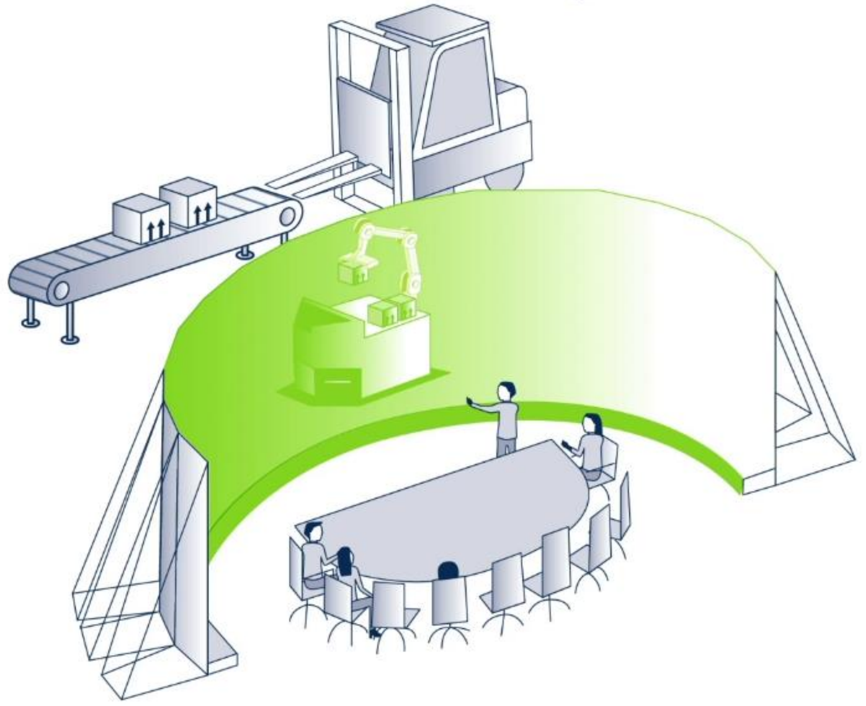


FABRIEK VOOR DE TOEKOMST
MACHINEBOUW & MECHATRONICA

Applicatielab
Smart Production Organisation

Hoe stuurt u uw totale productieorganisatie slim en optimaal aan?



De openingen bijwonen is **gratis**, maar wij vragen u wel in te schrijven via www.fabriekenvoordetoekomst.be/openinglabs

Meer informatie: johannes.cottyn@ugent.be

QUESTIONS

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