Course Project

Modelling and Simulation of Mechatronics Systems

Students: Antonello Zamboni, Giorgio Checola

Professor: Francesco Biral

Università degli Studi di Trento

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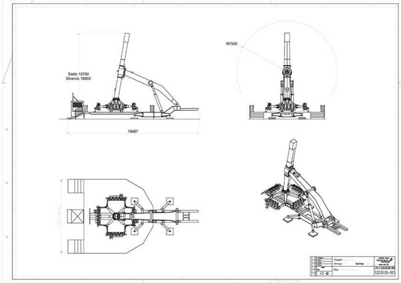
PEGASUS

CHARACTERISTICS

- 4 seats for vehicle, for a total number of 16 passengers
- Both crown and vehicles rotate of 360°
- While operating:
  - → the rotating arm is slightly inclined
  - → Lifting arm reaches the maximum height

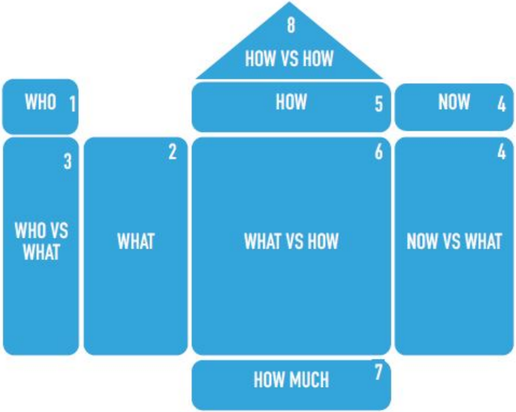
"WHAT WE WANT FROM THE SYSTEM?"

GOALS: Studying the system performing a *kinematic* and *dynamic* analysis and design an appropriate model to evaluate the system performance



Quality Function Deployment (QFD)

Following the **House of Quality** procedure to better develop engineering specifications and to satisfy the costumer needs



System requirements

We have extracted the following system requirements:

- Enjoyable ride
- Space optimization
- Suitable for passengers of different sizes
- Durability of the structure
- Low energy consumption
- Passenger safety
- Reduced motion sickness after the ride
- Maximization of gains

Engineering specifications: KINEMATICS

System requirements	Engineering Specifications	Target value	Unit
Space optimization	Workspace	$L = 18 \div 19$ $W = 16 \div 17$ $H = 16 \div 18$	m
Reduced motion sickness	Maximum angular velocity	$9 \div 12$	rpm
Maximization of gains	Theoretical hourly capacity	$300 \div 380$	pph
Passengers of different sizes Passenger safety	Passengers' height	< 1.90	m
Passenger safety Enjoyable ride	Maximum Acceleration	$Gx = -2 \div +2\,g$ $Gy = -2 \div +2\,g$ $Gz = -1.5 \div +4\,g$	$\frac{m}{s^2}$
Low energy consumption Durability of the structure Enjoyable ride	Time at max acceleration	< 5	s

Engineering specifications: DYNAMICS

System requirements	Engineering specifications	Target value	Unit
Low energy consumption	Weight of the structure	$12000 \div 16000$	Kg
Low energy consumption	Power	$150 \div 200$	kW
Passengers of different sizes Durability of the structure Low energy consumption	Passengers' weight	< 130	Kg

TARGET VALUES (PART.1)

- **Workspace**: it's one of the most important engineering specification of the system
  - → https://www.technicalpark.com/amusement-rides/pegasus-16/
  - → https://www.technicalpark.com/amusement-rides/pegasus-30/
  - → https://www.zamperla.com/products/midi-discovery/
- **Weight of the structure**: the weight range has been chosen from a competitor ride of similar dimensions: Revolution 32
- **Maximum acceleration**: the values has been chosen according to the study

  Establishing criteria for safe g-force levels for passenger carrying amusement rides (pag.7)

TARGET VALUES (PART.2)

- **Time at maximum Acceleration**: appropriate values derived from the paper High Acceleration and the Human Body (pag.11)

- **Maximum angular velocity**: from Artificial Gravity (pag. 11) angular velocities can cause motion sickness due to Coriolis forces and cross-coupled angular acceleration.

  → Artificial Gravity (pag.42)
  → https://www.fabbrigroup.com/portfolio-item/inversion/#1506782277732-1147f336-5b75
  → https://www.technicalpark.com/amusement-rides/pegasus-16/

- **Theoretical hourly capacity**: we obtained the ranges comparing different competitors:

  → https://www.zamperla.com/products/midi-discovery/
  → https://www.fabbrigroup.com/portfolio-item/inversion/#1506782277732-1147f336-5b75
  → https://www.rideentertainment.com/extreme-rides/booster/

TARGET VALUES (PART.3)

- **Power**: we selected the target from these competitors:
  - → https://www.rideentertainment.com/extreme-rides/booster/
  - → https://www.rideentertainment.com/extreme-rides/chaos-pendle/
- **Passengers' height**: we imposed the limit of man 95 percentile:
  - → https://www.rideentertainment.com/extreme-rides/chaos-pendle/
  - → https://www.rideentertainment.com/extreme-rides/booster/
  - → https://dqydj.com/height-percentile-calculator-for-men-and-women/
- **Passengers' weight**: we imposed the limit of man 95 percentile:
  - → https://dqydj.com/weight-percentile-calculator-men-women/
  - → Revolution 32

PERFORMANCE INDICES

Performance Index	Target value	Unit
Workspace	$L = 18 \div 19$ $W = 10 \div 13$ $H = 16 \div 18$	m
Theoretical hourly capacity	$300 \div 380$	pph
Acceleration profile		$\frac{m}{s^2}$
Power	$150 \div 200$	KW

WEIGHTING MATRIX

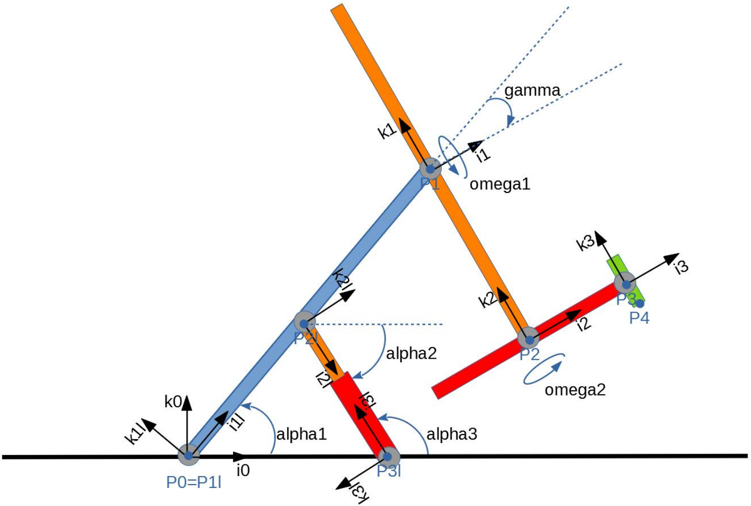
Engineering specifications

Specification	Rate
Maximum acceleration	9
Workspace	9
Maximum angular velocity	8
Theoretical hourly capacity	6
Time at max acceleration	5
Passengers' weight	4
Passengers' height	4
Power	3
Weight of the structure	2

Performance indices

Performance index	Rate
Workspace	9
Acceleration Profile	7
Theoretical hourly capacity	5
Power	2

KINEMATIC ANALYSIS



Initial considerations

We did the following assumptions:

- Rheonomous constraint for independent coordinates
  - $\rightarrow$ Constant angular velocities
- Lifting arm oriented along the X-axis
- Seats of passengers fixed to the Vehicle
- Lifting arm and Rotating arm analysed separately
- Rotating arm fixed with an angle of 30° with respect to the perpendicular to the Lifting arm

Recursive Approach

- P0: origin on the ground
- P1: Lifting - Rotating arm revolute joint
- P2: Rotating arm - center of the Vehicle revolute joint
- P3: Vehicle - last Seat revolute joint
- P4: foot of the passenger

Since we consider the Lifting arm as fixed we have only two moving bodies: the Rotating arm (body1) and the Vehicle (body2)

Being an open chain mechanism, there are no constraint equations with this formulation

Global Approach

Absolute coordinates and Euler angles sequence

$\rightarrow$ $rot(Y, phi).rot(X, theta).rot(Z, psi)$

And as independent coordinates:

$\rightarrow$ $psi2(t)$, $theta1(t)$

Constraint Equations

- I Revolute joint
  (Lifting arm - Rotating arm)
- II revolute joint
  (Rotating arm - Vehicle)
- Time law of independent coordinates:

  $PHI\_t := [theta\mathbf{1}(t) - omega\mathbf{1} \cdot t,\ psi\mathbf{2}(t) - omega\mathbf{2} \cdot t]$

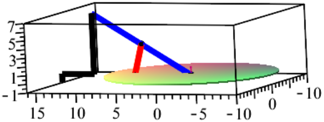
Newton-Raphson method

Numerical approach because of the high number of constraint equations

Lifting Arm

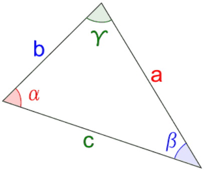
3-body system

- → Lifting arm (body1)
- → Piston (body2)
- → Chamber (body3)



One degree of freedom: s(t)
Initial condition of $alpha1 = 30°$
Final condition $alpha1 = 50°$

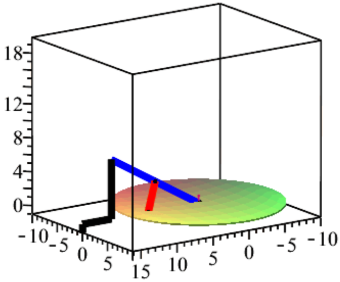
By means of Carnot's theorem we computed these lengths:
$L1 = 14\ m$, $L2 = 3.62\ m$
$L3 = 3.62\ m$, $Lp = 7\ m$



$$b^2 = a^2 + c^2 - 2ac\,cos(\beta)$$

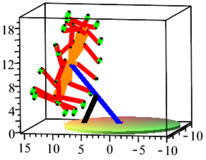
Animation of the mechanism

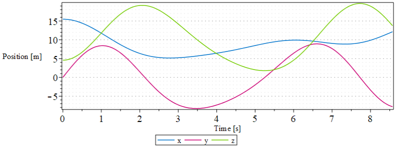
By connecting the Lifting arm with the main part of the system we got the final kinematic model of our amusement ride:



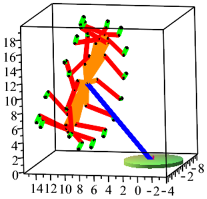
Position and Workspace Analysis

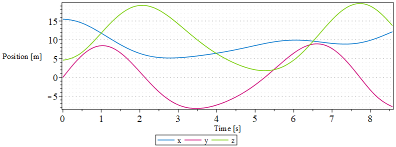
Recursive





Global

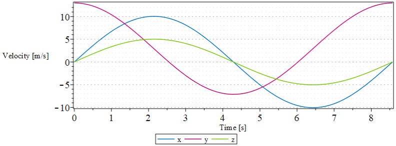


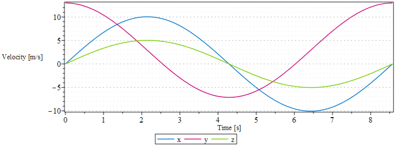


Velocity and Acceleration Analysis

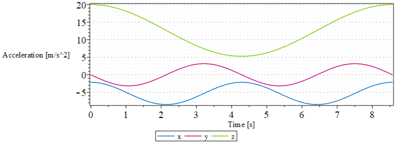
Recursive | Global

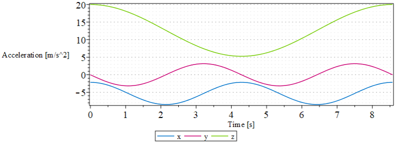
Velocity perceived by the passenger





Acceleration perceived by the passenger





Check of Engineering Specification (part.1)

- **Workspace**: the results are obtained by observing the workspace configuration and the plots of position of the passenger

Engineering Specifications	Target value	Final value	Unit
Workspace	$L = 18 \div 19$ $W = 16 \div 17$ $H = 16 \div 18$	$x \simeq 15.5$ $y \simeq 17$ $z \simeq 20$	m

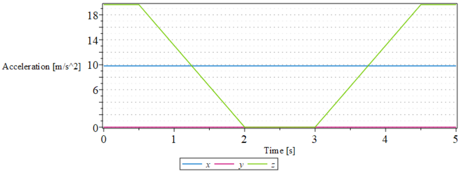
Parameters

- Length of the Lifting arm $L = 14\ m$
- Radius of the Vehicle $L2 = 4\ m$
- Angle Lifting arm $alpha = 50°$
- Half Rotating arm $L1 = 7\ m$
- Length of half Seat $L3 = 1\ m$
- Angle Rotating arm - Lifting arm $gamma = 30°$

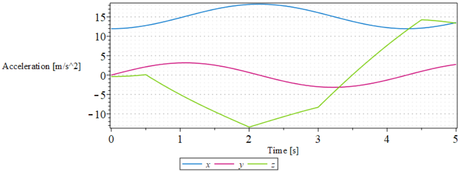
Check of Engineering Specification (part.2)

▷ **Acceleration profile**:
1. along Z-axis: max acceleration at minimum height and no acceleration at maximum height
2. along Y-axis: zero
3. along X-axis: constant acceleration $1\,g$

Target profile



Difference between real profile and target profile



Check of Engineering Specification (part.3)

- **Maximum angular velocity**: 2 different angular velocities (ω_1 for Rotating arm and ω_2 for Crown)

ω_1	$9 \div 12$	10	*rpm*
ω_2	$9 \div 12$	7	*rpm*

- **Theoretical hourly capacity**:

Theoretical hourly capacity	$300 \div 380$	320	*pph*
Ride time		3	*min*

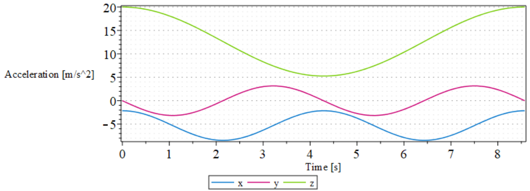
Check of Engineering Specification (part.4)

- **Maximum acceleration**: the results are obtained from the plots of the accelerations perceived by passengers

Gx	$-2 \div +2\,g$	$\simeq -8.5 \div -2.1$	
Gy	$-2 \div +2\,g$	$\simeq -3.2 \div +3.2$	$\frac{m}{s^2}$
Gz	$-1.5 \div +4\,g$	$\simeq 5 \div 20$	

- **Time at max acceleration**: in the worst case it is around 1 sec

Time at max acceleration	< 5	1	s



DYNAMICS ANALYSIS
INITIAL CONSIDERATIONS

We did the following assumptions:

- Recursive formulation with Lagrange approach
- Iron density and rectangular prism consideration for masses
  - $\rightarrow$ $S = 0.04\ m^2$
  - $\rightarrow$ $\rho = 7870\ \frac{kg}{m^3}$
- Rods approximation for bodies with mass distributed along an axis
- Seats not fixed to the Vehicle
- Start with a vertical seat
- Constant angular velocities for independents coordinates
- Lifting arm and Rotating arm analyzed separately

Lagrange Approach

Definition of the bodies

- Rotating arm
- Vehicle
- Seat

Actuation forces

- C1: motor torque which produce a rotation of the Rotating arm
- C2: motor torque which produce a rotation of the vehicle

Parameters

- m: mass of the body
- Ixx,Iyy,Izz,Ixy,Ixz,Iyz: moments of inertia respect each axis
- $lambda1, lambda2$: lagrange multipliers

Two different approaches

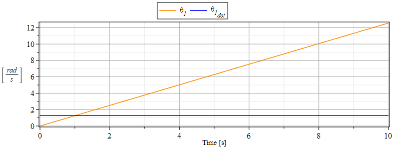
→ Constraint imposed by Lagrange multipliers considering zero external forces. Comparison with different solving approaches:

- Maple solver
- Matlab: Index reduction
- Matlab: Projection method
- Matlab: Baumgarte stabilization

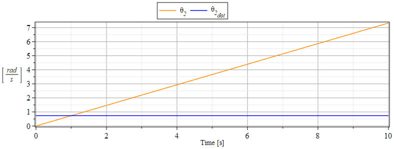
→ Inverse dynamics substituting the constraint directly in the equations

Maple solver: DAE

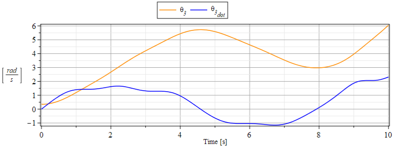
θ_1 and $\dot{\theta}_1$



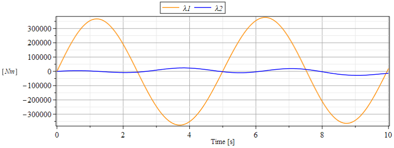
θ_2 and $\dot{\theta}_2$



θ_3 and $\dot{\theta}_3$

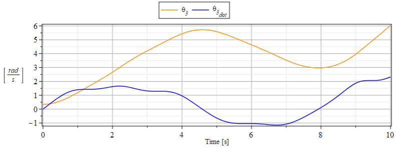


λ_1 and λ_2

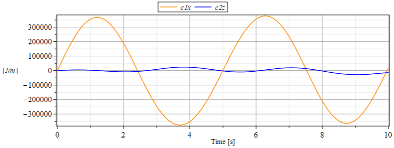


Maple solver: inverse Dynamics

θ_3 and $\dot{\theta}_3$



C_1 and C_2



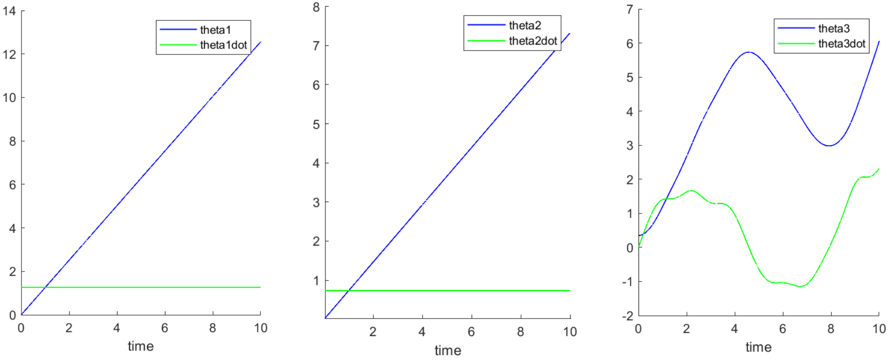
- The values for *theta*3 are very similar to the one obtained from the DAE
- We have the confirmation that the Lagrange multipliers coincide with the torques

Analysis with MATLAB

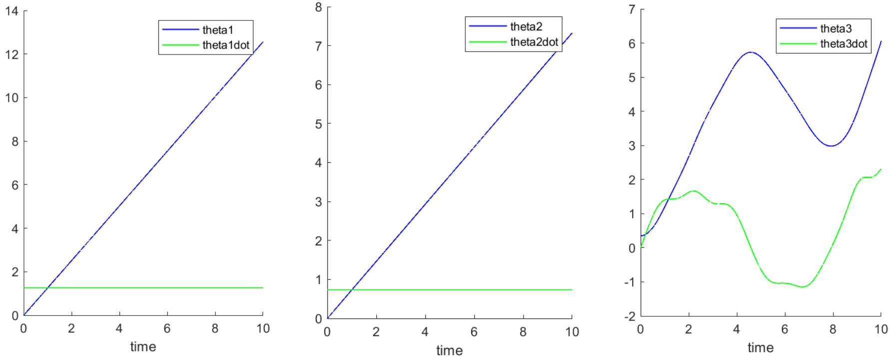
By means of professor Bertolazzi's libraries we performed the following operations:

- Index reduction from index 3 to index 1
- Transcription of the mechanism model from Maple to Matlab
  - mass matrix
  - hidden constraint
  - generalized forces
  - jacobian of the RHS (implicit methods)
- Solving of the obtained DAE with:
  - implicit method (Radau)
  - projection method (Radau_P)
  - Baumgarte stabilization (Heun)

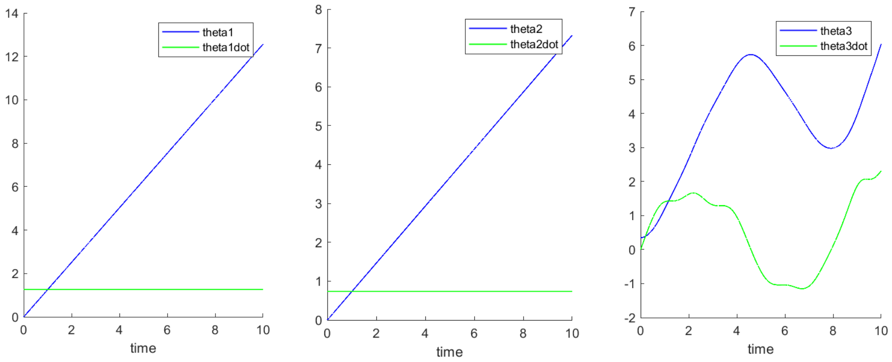
RESULTS IMPLICIT METHOD



RESULTS Projection method



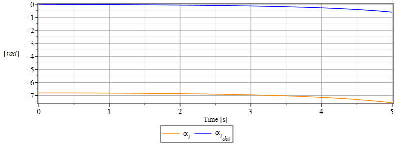
RESULTS BAUMGARTE STABILIZATION

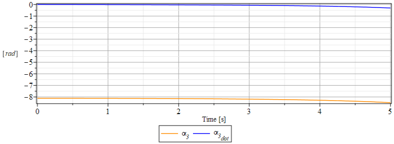


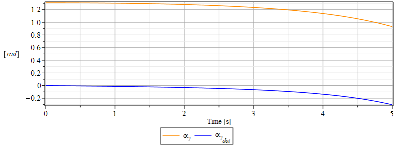
Lifting Arm

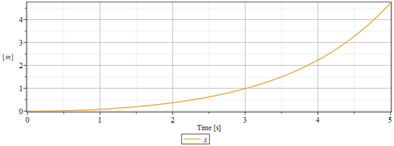
We have the following differences:

- closed-loop mechanism (3 constraint equations)
- no rheonomous constraint
- constant force of the prismatic joint $F_0 = 50000\ N$
- independent coordinate $s(t)$









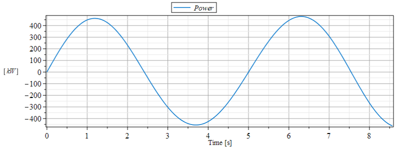
Check of Engineering Specification

- **Weight of the structure**: summing all masses we got:

$$M_{tot} = 16762.13kg$$

- **Power**: sum of the power of the torque C1 and C2

We can't compare it directly to the chosen index performance for the following reasons :



- this power is purely mechanical
- oscillating power and average(RMS) has to be computed
- negative power during deceleration has not to be considered

Engineering Specifications	Target value	Final value	Unit
Weight of the structure	$12000 \div 16000$	$\simeq 16700$	kg
Power	$150 \div 200$	$-450 \div 450$	kW

THANKS FOR THE ATTENTION