Lecture «Robot Dynamics»: *Introduction*

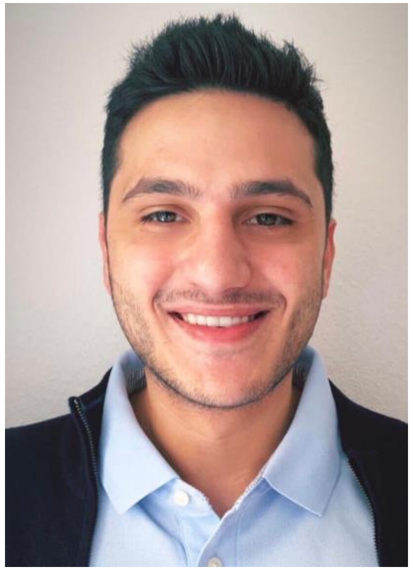
151-0851-00 V

Lecture HG G5: Tuesday 10:15 – 12:00, every week

Exercise HG G5: Wednesday 8:15 – 10:00, according to schedule

Marco Hutter, Roland Siegwart

Lecturers



Marco Hutter
Prof. Dr.

Roland Siegwart
Prof. Dr.

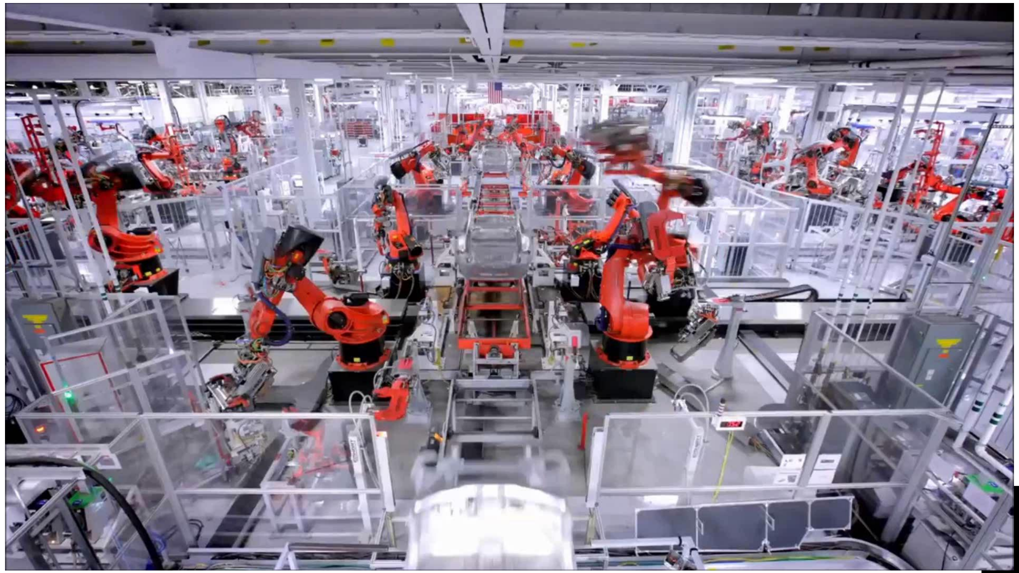
Jean-Pierre Sleiman
PhD student, TA

ETH zürich

Reason for absence

Joint live on DARPATV

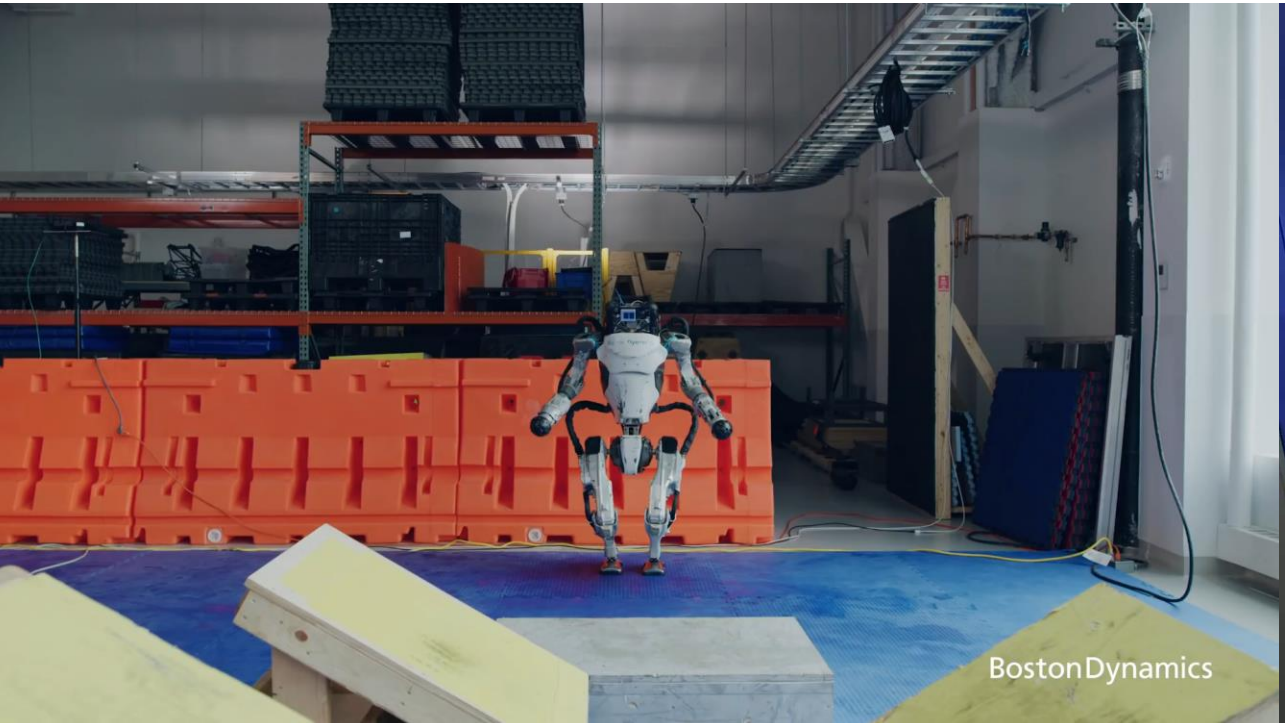
Robotics
The natural evolution of automation



- Huge demand
- Growing market and applications
- Big investment by big companies

Modern mobile manipulators by Boston Dynamics

Some of the most versatile dynamic robots



Modern mobile manipulators by Boston Dynamics

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Modern mobile manipulators by Boston Dynamics

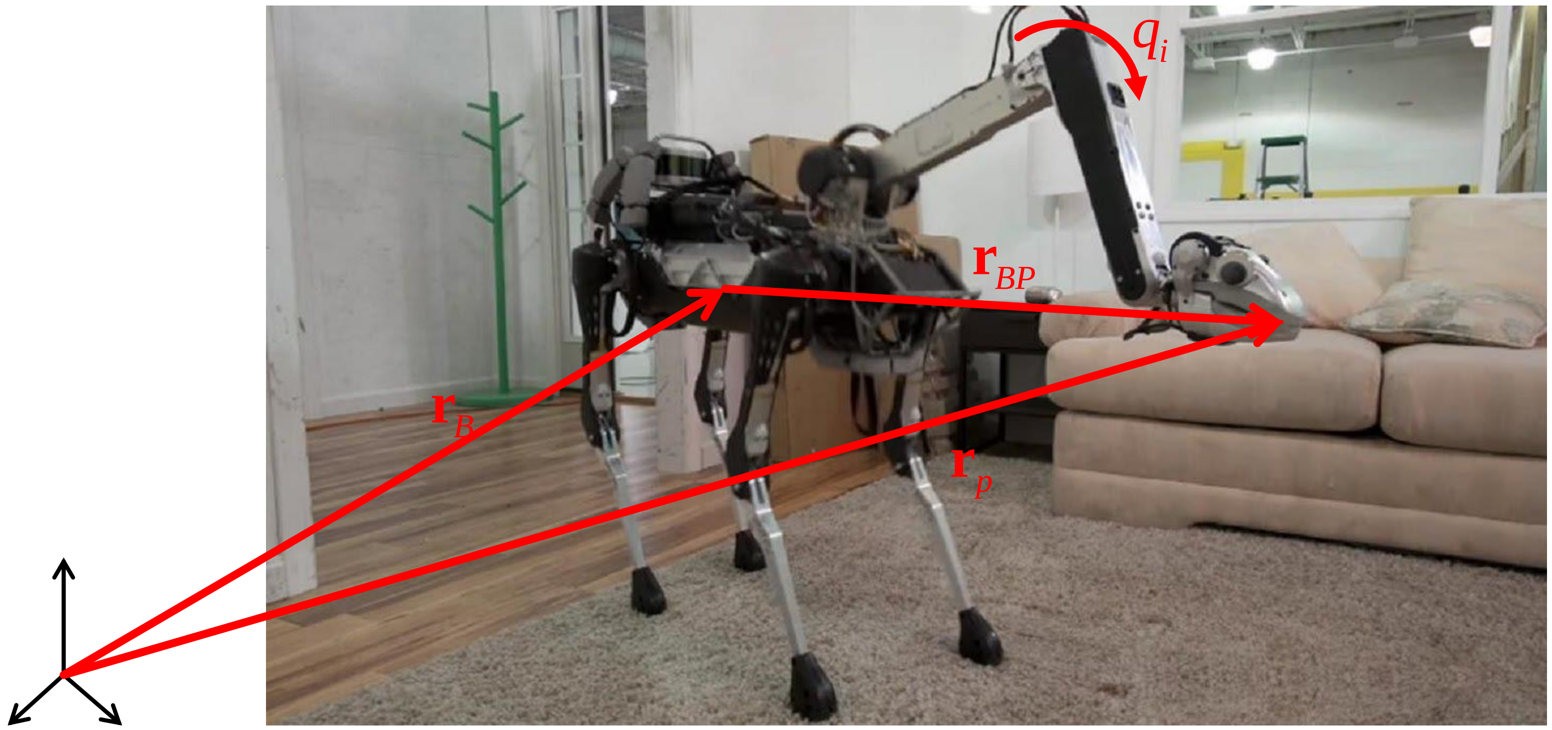
Some of the most versatile dynamic robots

Why should I understand «Robot Dynamics»

- Robot Dynamics = learn how to model the physical behavior
  - Simulation *(how does my system behave if certain actuator commands are given?)*
  - Control *(inverting causality: if I want to move the robot in a specific way, what actuator commands are necessary?)*
  - Design (what are the dynamic loads on my structure?)
  - Optimization (what are the optimal dimensions of my vehicle?)
  - Actuation (what torque, speed, power etc. is required to move the system as I want?)

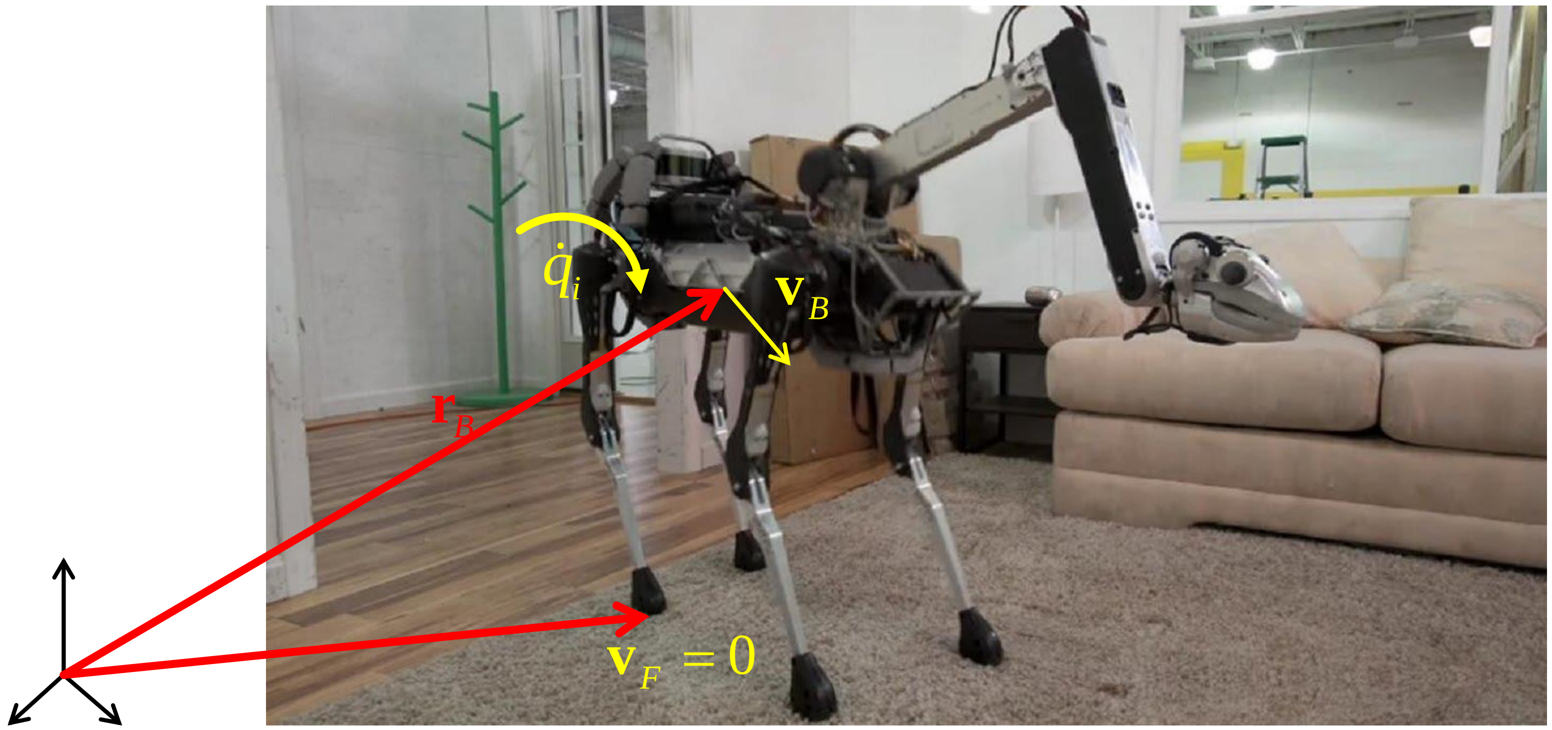
Kinematics, Dynamics, and Control of Quadruped + Manipulator

- Joint position ⬄ task space position $\mathbf{r} = \mathbf{r}(\mathbf{q})$



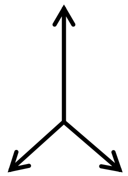
Kinematics, Dynamics, and Control of Quadruped + Manipulator

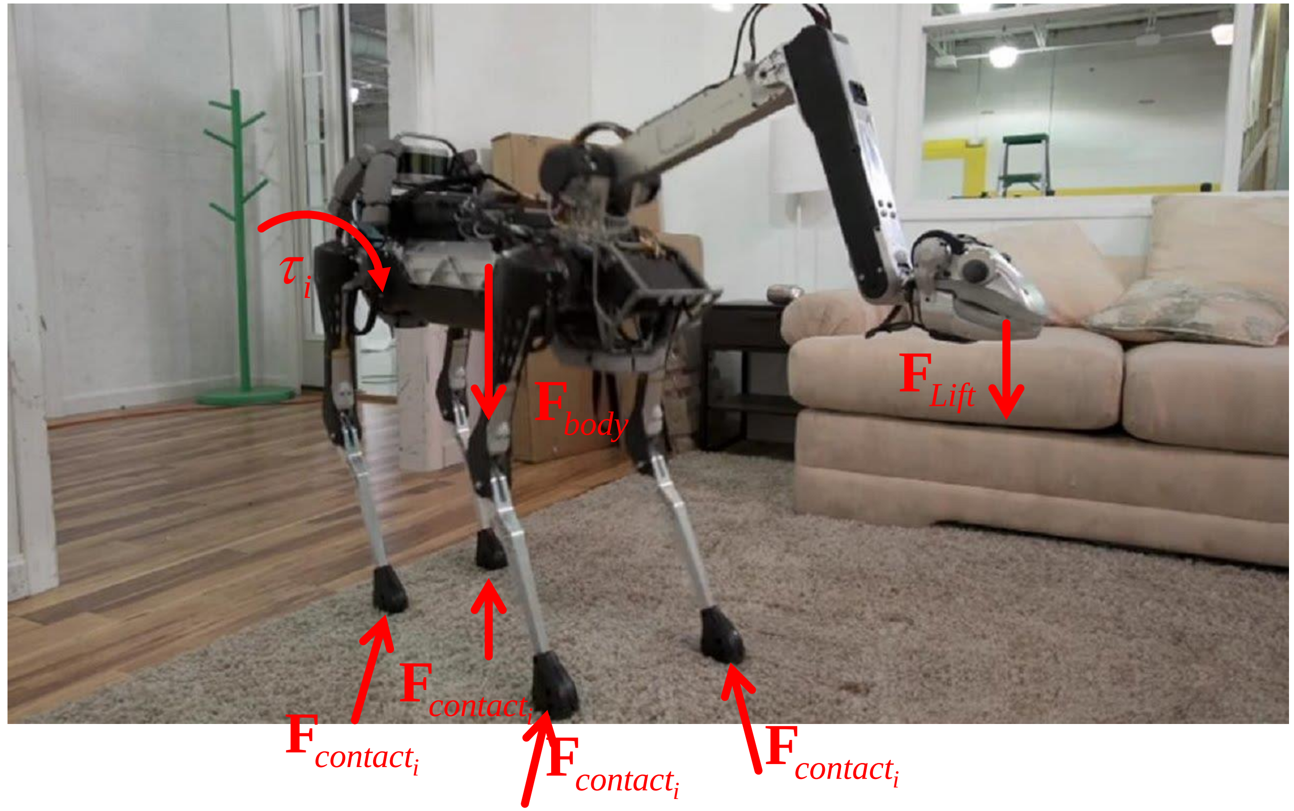
- Joint velocity ⇔ task space velocity $\dot{\mathbf{r}} = \mathbf{J}\dot{\mathbf{q}}$



Kinematics, Dynamics, and Control of Quadruped + Manipulator

- Joint torque ⬄ motion / external forces $\mathbf{M}\ddot{\mathbf{q}} + \mathbf{b} + \mathbf{g} + \mathbf{J}_{ext}^T \mathbf{F}_{ext} = \mathbf{S}^T \boldsymbol{\tau}$





Robot Dynamics
Lecture goals

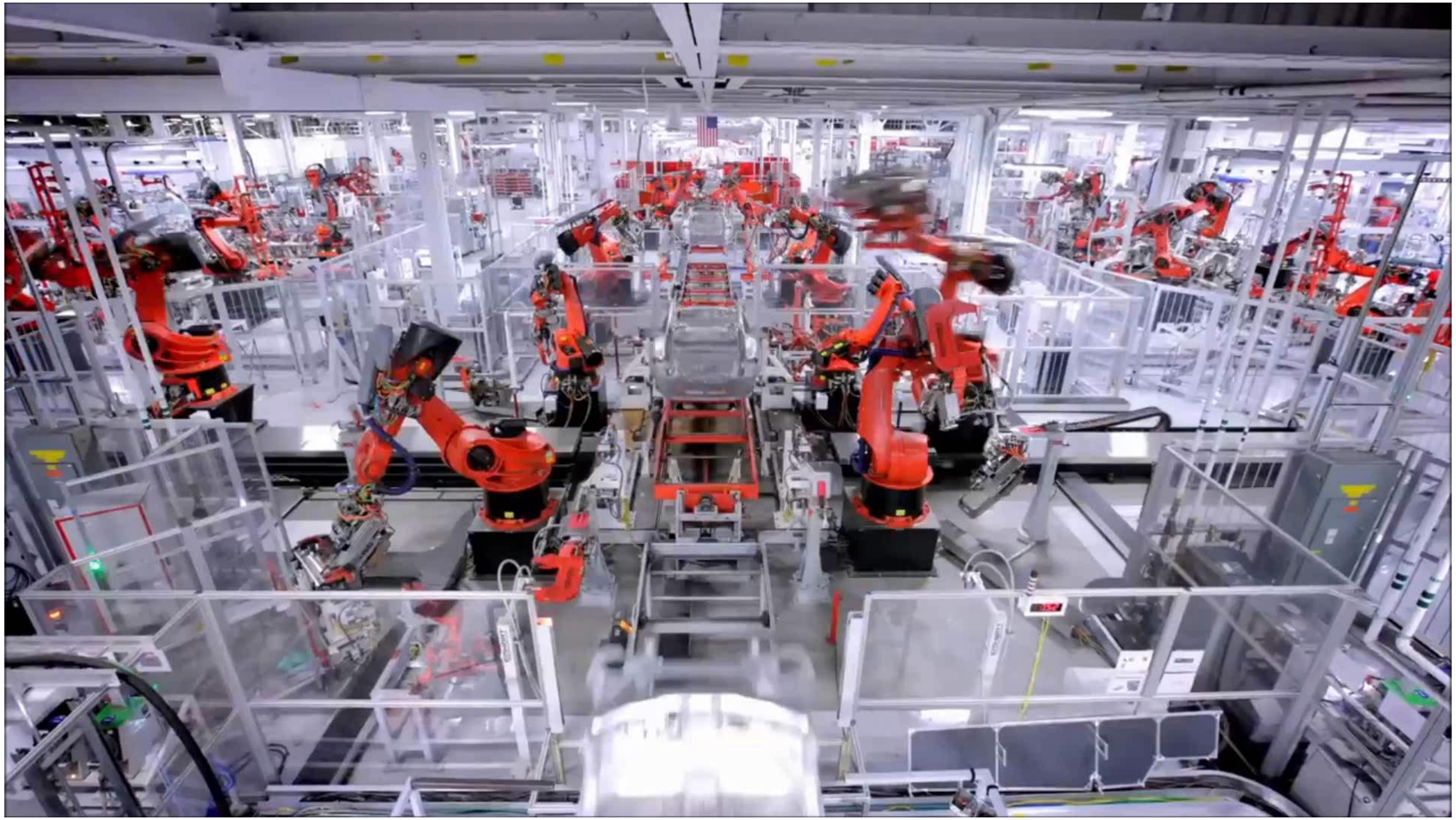
$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{b} + \mathbf{g} + \mathbf{J}_{ext}^{T}\mathbf{F}_{ext} = \mathbf{S}^{T}\boldsymbol{\tau}$$

- Kinematic and dynamic modeling of robotic systems:
  - Manipulators (position and force control)
  - Legged robots
  - Rotary wing systems
  - Fixed wing airplanes
- Objective of the course
  - Deepening an applied understanding of how to model the most common robotic systems
  - Extending the background in kinematics, rotations, and dynamics of multi-body systems
  - Modeling of actuation forces
  - Apply the models in control
- Provide tools to work in *simulation, planning and control* of robotic systems

Real systems!
not planar toy problems

21.09.2021	Intro and Outline	Course Introduction; Recapitulation Position, Linear Velocity			
28.09.2021	Kinematics 1	Rotation and Angular Velocity; Rigid Body Formulation, Transformation	29.09.2021	Exercise 1a	Kinematics Modeling the ABB arm
05.10.2021	Kinematics 2	Kinematics of Systems of Bodies; Jacobians	06.10.2021	Exercise 1a	Differential Kinematics of the ABB arm
12.10.2021	Kinematics 3	Kinematic Control Methods: Inverse Differential Kinematics, Inverse Kinematics; Rotation Error; Multi-task Control	13.10.2021	Exercise 1b	Kinematic Control of the ABB Arm
19.10.2021	Dynamics L1	Multi-body Dynamics	20.10.2021	Midterm 1	Programming kinematics with matlab
26.10.2021	Dynamics L2	Floating Base Dynamics	27.10.2021	Exercise 2a	Dynamic Modeling of the ABB Arm
02.11.2021	Dynamics L3	Dynamic Model Based Control Methods	03.11.2021	Exercise 2b	Dynamic Control Methods Applied to the ABB arm
			10.11.2021	Midterm 2	Programming dynamics with matlab

Application 1: Industrial Robots



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09.11.2021	Legged Robot	Dynamic Modeling of Legged Robots & Control	10.11.2021	Midterm 2	Programming dynamics with matlab
16.11.2021	Case Studies 1	Legged Robotics Case Study	17.11.2021	Exercise 3	Legged robot
23.11.2021	Rotorcraft	Dynamic Modeling of Rotorcraft & Control			
30.11.2021	Case Studies 2	Rotor Craft Case Study	01.12.2021	Exercise 4	Modeling and Control of Multicopter
07.12.2021	Fixed-wing	Dynamic Modeling of Fixed-wing & Control			
14.12.2021	Case Studies 3	Fixed-wing Case Study (Solar-powered UAVs - AtlantikSolar, Vertical Take-off and Landing UAVs – Wingtra)	15.12.2021	Exercise 5	Fixed-wing Control and Simulation
21.12.2021	Summery and Outlook	Summery; Wrap-up; Exam			

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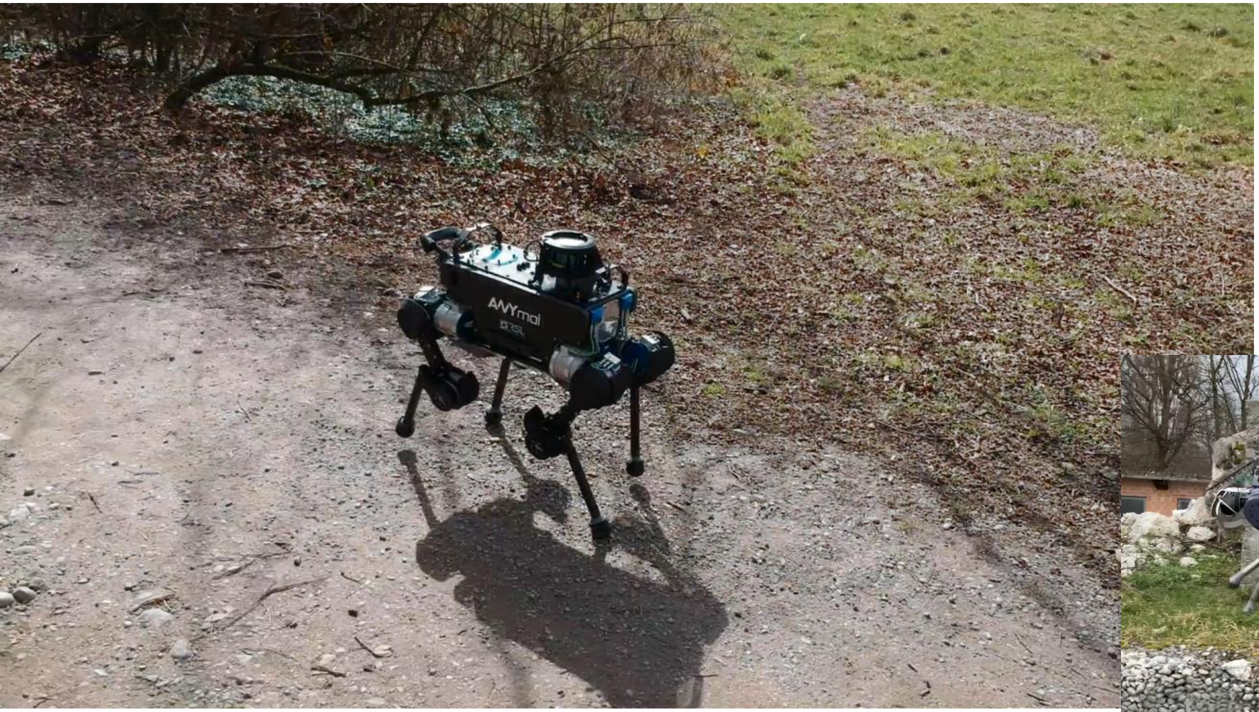
ETH Quadrupedal Robots

- Hybrid dynamics (impulse)
- Contact constraints
- Constraint constistent dynamics
- Internal forces
- …



ETH Quadrupedal Robots

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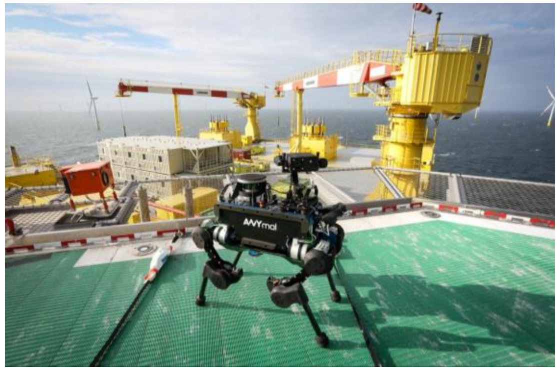
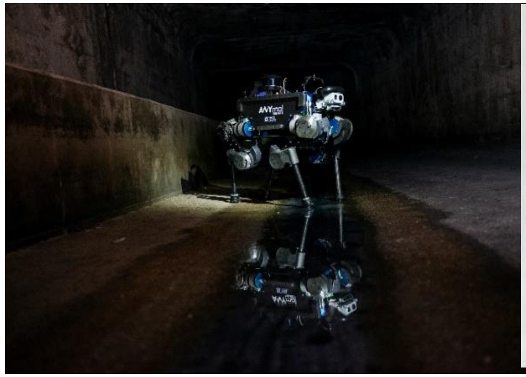
- …

ANYmal case studies





Industrial
- Inspection/Surveillance

EU H2020 THING
- Sewer
- Copper mine

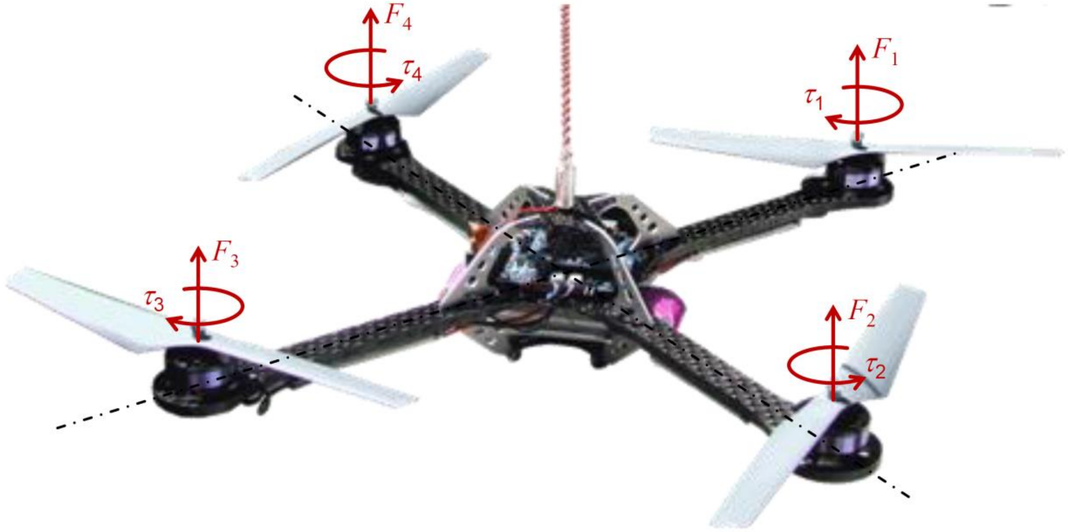
NCCR + ARCHE
- Search and Rescue

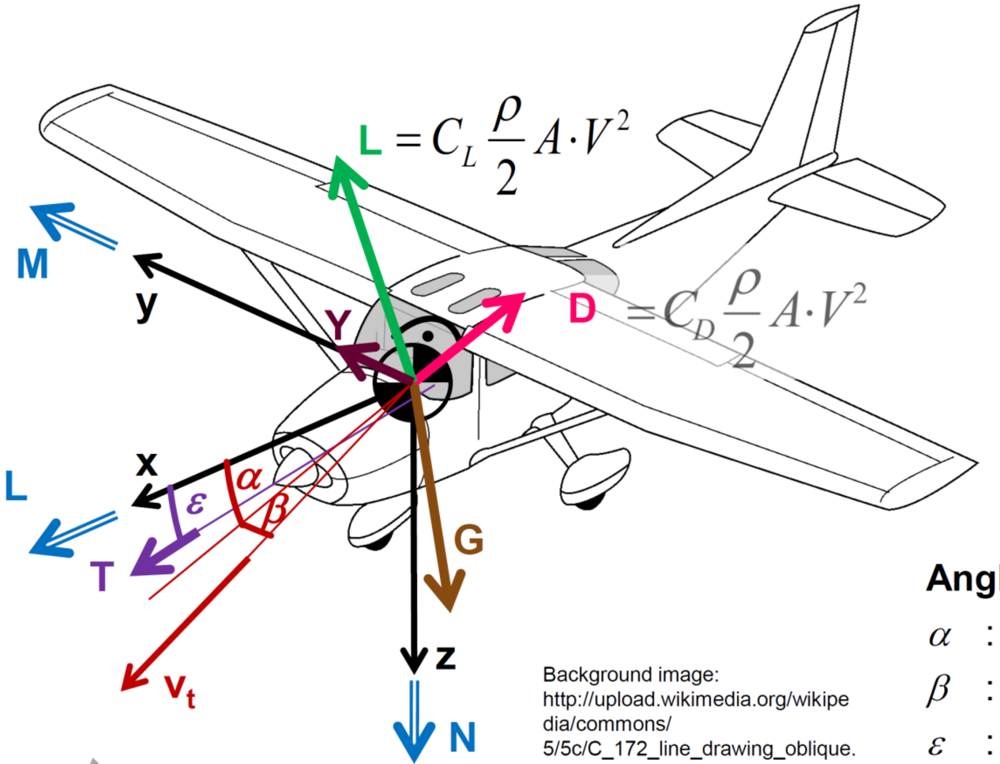
DARPA SubT
- Underground exploration

Dynamics of Airplane and Rotorcraft

- Understanding system dynamics is essential for control

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{b} + \mathbf{g} + \mathbf{J}_{ext}^{T}\mathbf{F}_{ext} = \mathbf{S}^{T}\boldsymbol{\tau}$$





Background image: http://upload.wikimedia.org/wikipedia/commons/5/5c/C_172_line_drawing_oblique.

Moments

L : Roll moment

M : Pitch moment

N : Yaw moment

Forces

L : Lift

D : Drag

Y : Sideslip force

T : Thrust

G : Weight

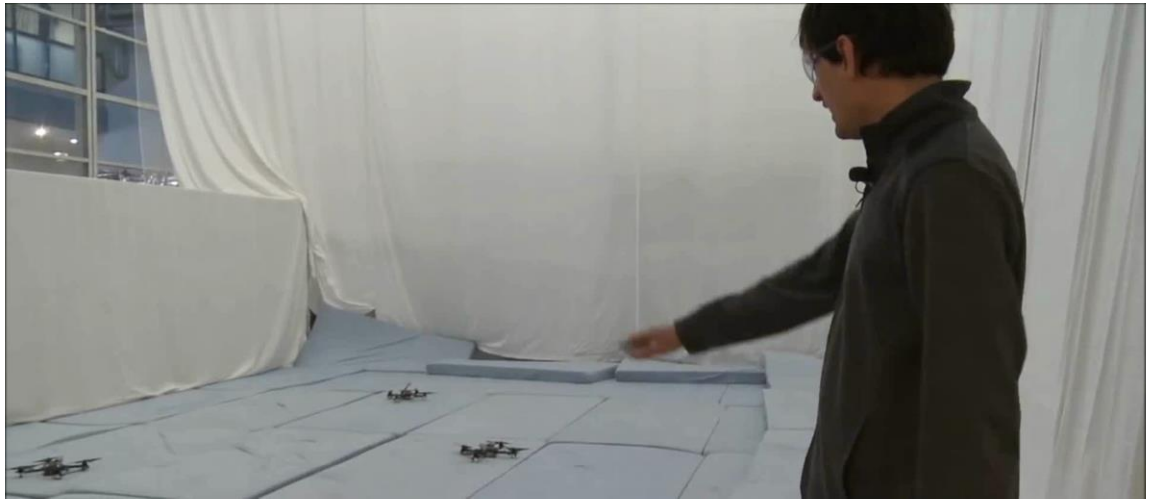
Angles

α : Angle of attack

β : Sideslip angle

ε : Thrust-vector angle

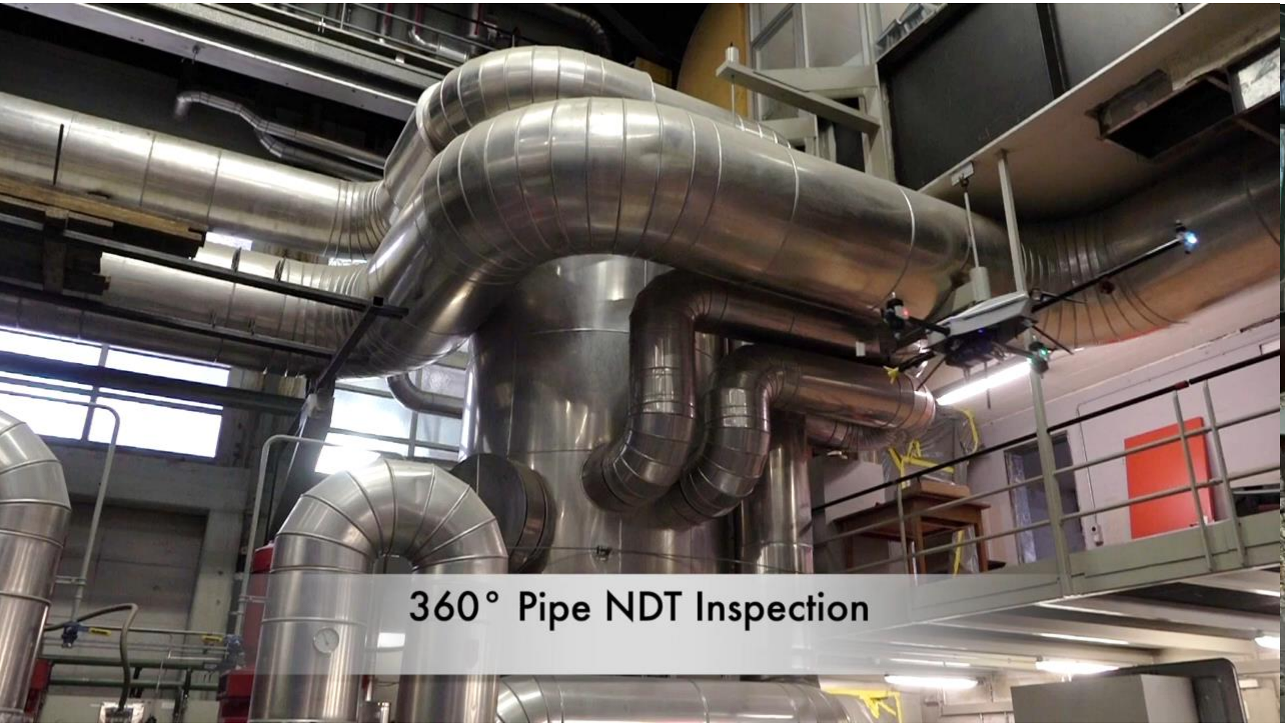
Dynamics and Control of Flying Vehicles



Flying machine arena, IDSC, ETH Zurich

Vertiy

Dynamics and Control of Flying Vehicles



Atlatic Solar
Arctic Ice Inspection

Goal and Learning Objectives

Overall Goal

- Students can kinematically and dynamically model typical robotic systems.

Learning objectives

1. Students can analyze and apply forward and inverse (differential) kinematics of articulated robotic systems in 3D
2. Students can apply the most common methods for deriving the dynamic model for articulated robotic systems in 3D
3. Students apply dynamic model-based control methods to regulate motion and interaction
4. Students have a broad understanding on challenges in modeling and controlling the most common robotic systems such as robot arms, legged robots, rotary and fixed wing systems

Learning Objectives Details

1. **Students can analyze and apply forward and inverse (differential) kinematics of articulated robotic systems in 3D**
   - S1: Students understand concepts of vectors, positions, velocities, and frames
   - S2: Students can apply rotation matrices and different parameterizations to describe body orientations
   - S2: Students understand the difference between time differentiation of position/orientation parameterization and linear/angular velocities
   - S3: Students understand the concepts of generalized coordinates and joint and tasks space. They are able to describe the forward kinematics of multi-body systems
   - S4: Students understand the concept for differential kinematics and apply it for inverse kinematics problems
   - S4: Students can apply hierarchical least square optimization for multi-task control
   - EX1+2: Students can implement the learned tools in matlab to kinematically model and control a robot arm

Learning Objectives Details

2. **Students can apply the most common methods for deriving the dynamic model for articulated robotic systems in 3D**
   - S5: Students can apply NE, projected NE, and Lagrange II to derive the equations of motion for articulated robotic systems
   - S6: Students can apply the learned methods to create the equations of motion for floating base systems; they can handle impact, contact constraints and support consistent equations of motion

3. **Students apply dynamic model-based control methods to regulate motion and interaction**
   - S7: Students can apply different variants of inverse dynamics control methods to rregulate motion and interaction
   - Ex3+4: Students can implement the learned tools in matlab to dynamically model and control a robot arm

Learning Objectives Details

4. **Students have a broad understanding on challenges in modeling and controlling the most common robotic systems such as robot arms, legged robots, rotary and fixed wing systems**
    - S1+S14: Students get an overview on the different challenges and methods associated with modeling and controlling robotic systems
    - S8+9 +Ex5: Students can apply the introduced methods to model and control multi-legged robots. They are able to properly handle contact constraints using soft and hard contact models
    - S10+11 +Ex6: Students can apply the introduced methods to model and control rotary wing systems based on a linearization of the system dynamics. They understand and can apply basic principles of thrust generation and.
    - S12+13 +Ex7: Students can apply the introduced methods to model and control fixed wing systems. They understand and can apply basic principles of uplift and drag generation.

Lecture Material
online course HS 2020

- Official lecture material on moodle
  - Script on kinematics and dynamics
  - Slides + Quiz
  - Exercise exams
- Possible but not necessary class preparation
  - Read the sections in the script
- Online option
  - Video segments for theory + recordings of quiz sessions from HS 2020 are online
  - Watch the theory segments
  - Conduct the quiz
  - Watch the live session
- Additional readings
  - Handbook of Robotics (Siciliano, Khatib)
    - http://link.springer.com/referencework/10.1007/978-3-540-30301-5
  - Robotics – Modelling, Planning and Control (Siciliano, Sciavicco, Villani, Oriolo)
    - http://link.springer.com/book/10.1007%2F978-1-84628-642-1

Lecture Setup

- Lecture (HG G5)
  - Lecture is split in some theory blocks
  - Quizzes (similar to what you can expect in exam)

Quiz

- Exercise (HG G5)
  - Short recapitulation of lecture [Jean-Pierre Sleiman]
  - Real problems at robotic systems (e.g. ABB industrial arm)
  - Matlab => use your own laptop
- Two optional intermediate exams (at ETH, count 15% each if improving)
- Case Studies
  - State of the art engineering and research at selected examples
  - Not primarily relevant in exams (only some multiple choice questions)

Lecture Rules - Questions

- Use moodle for Q&A
  - https://moodle-app2.let.ethz.ch/course/view.php?id=15356
  - There are different sections for *general, lecture,* and *exercise_i*
    - *Use the corresponding Q&A forum*
    - *Check the OLD-Q&A forum with questions from last year*
  - Answer questions of your peers (the most active supporters will get a small gift at the end of the semester)
  - TAs and me will take care of the remaining questions
  - Your Questions help us to revisit topics in lecture and exercise class (post questions until Monday noon)
- Write an email
  - Personal meetings with me or TAs

Exam

- Exercise exam online available
- Content
  - Multiple choice questions
    - Up to half of the questions can be defined by you
    - Everyone can post up to 1 question after every lecture on moodle
    - Rest will come from us
  - Kinematics and dynamics
    - Similar to the quizzes in the lecture
  - Robot specific
    - Legged robots
    - Rotor craft
    - Fixed wing
- Intermediate exams (counts 15% each if improving)
  - Similar to exercise with MATLAB