Control of legged robots

Scientific Disciplinary Sector: ING-INF/04

Number of hours: 15 (+15 optional)

Credits (CFU): 4 (+ 4 optional)

Schedule 1 part: 3-hour sessions with 15 min break

Schedule 2 part: TBD

Teacher: Dr. Michele Focchi

Contacts: michele.focchi@iit.it

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Structure of the course

Summary 1 part:

This course will provide a broad overview on the most common control strategies for fixed-based robots. Then follows an extension to floating based robots with details on how to model their dynamics.
Several whole-body control formulations are also presented.

Summary 2 part:

This course will introduce modern methods for robotics movement generation based on numerical optimal control. An introduction to approximated models is also given (Linear Inverted Pendulum and Centroidal Dynamics). It will also contain hands-on exercises for real robotic applications such as walking on flat terrain. The student will be able to generate a locomotion trajectory for the robot via optimization and track it with the controller implemented in Part1.

Prerequisites:

Dynamics & Robotics:

- Newtonian dynamics in 3D,
- Lagrangian mechanics,
- Jacobians
- coordinate systems: gymnastics for expressing vectors in different frames.

Linear algebra:

- intuitive grasp of concepts from linear algebra
- understanding of linear ordinary differential equations, and a moderate level of mathematical on maturity linear systems.
- Eigenvalues, eigenvectors, rank, nullspace, and positive definite matrices. (to refresh Gilbert Strang's lectures on linear algebra)

Control Systems:

- State space representation of linear systems
- Stability criteria for systems of linear ordinary differential equations.

Syllabus / content 1 part:

Basic Robot Control

A1. Joint Motion control (PD, PD + gravity, PID, Inverse Dynamics)
A2. non idealities in motion control (quantization noise, friction,gear boxes)
A3. Modeling of manipulators in contact (dynamics, rigid contact/ compliant contact)
A4. Operational space control (operational space inv. dynamics redundant manipulators, singularities)
A5. Redundant manipulators
A6. interaction control (direct force control, impedance control, inertia shaping)
A7. Representation of orientation, control of orientation

Floating based robots

B1. Introduction to floating based robots
B2. Modeling of legged robots: dynamics of Floating base robots (excess of coordinates or minimal coordinates modeling, non-holonomy of angular momentum)
B3. From floating base dynamics to Newton-Euler equations
B4. Building a simulator: contact Models (rigid contact compliant contacts), modeling of impact dynamics. Constrained dynamics obtained by contact null-space projection. Gauss principle of minimum effort.
B5. Constraint Inverse Dynamics

Advanced robot control

C1. Quasi static approach to control the Base or the Com, projection-based / QP-based formulation.
C2. full dynamics QP-based controller: joint space / task space inverse dynamics (Torque limits, acceleration limits, velocity limits, position limits)
C3. full dynamics QP-based controller in contact: friction constraints, reduced problem exploiting sparsity of the dynamics, implementation example

Lab sessions: Practical implementation of the theory

Activities:
Write code in Python (not much) / Analyze results (a lot) / Discuss

L1. Fixed base joint space control
L2. Fixed base operational space control (including orientation control)
L3. Contact consistent fixed base dynamics
L4. Floating base dynamics properties
L5. Floating base robot: control of CoM (quasi static approach), move CoM out of the support polygon, implement quasi-static QP controller.

SW Tools – you can code on:

- Virtual Machine (VirtualBox) to access the software for the lab sessions: https://www.dropbox.com/sh/8jc0zuw72zawnd8/AACthLLTgVQRpkJAzMd5Od9oa
- Your Ubuntu 16.04:
  - download Locosim project: https://github.com/mfocchi/locosim.git
  - follow install instructions in Readme.md

Organization of lectures:

July 7th: 14:30-17:30

July 9th: 14:30-17:30

July 10th: 14:30-17:30

July 13th: 14:30-17:30

July 15th: 09:30-12:30

July 21st: 14:30-17:30

Getting to know me

Research:

- Quadruped
- Control
- Locomotion
- Planning

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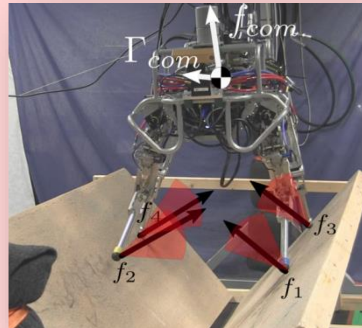
PhD



Whole-body control [AURO 17]

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Postdoc

Heuristic Planning [STAR 2019]

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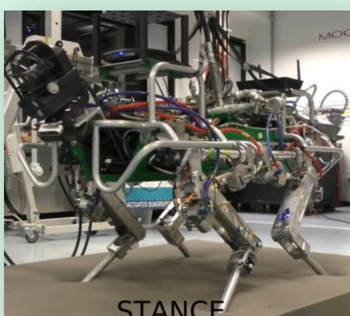
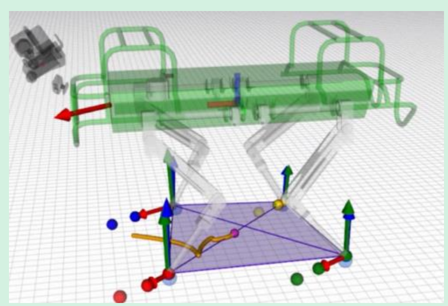
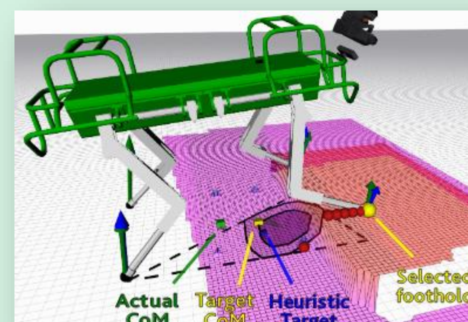
Researcher



Locomotion on soft-terrain [TRO 19]



MPC re-planning



Stability-based planning [TRO 19]

Resources (some of them free…):

Prerequisites:

- Introduction to Linear Algebra – Gilbert Strang (book) and course: https://ocw.mit.edu/courses/mathematics/18-06-linear-algebra-spring-2010/
- Feedback Control of Dynamic Systems - Gene F. Franklin, J. David Powell, Abbas Emami-Naeini

1 Part:

- A Mathematical Introduction to Robotic Manipulation - Richard M. Murray, Zexiang Li, S. Shankar Sastry.
- Introduction to Robotics: Mechanics and Control – J.Craig
- Kathib robotics video lectures: http://videolectures.net/stanfordcs223aw08_introduction_robotics/
- Robotics Modelling, Planning and Control - Siciliano, B., Sciavicco, L., Villani, L., Oriolo, G.
- Springer Handbook of Robotics (Chapter 2, Dynamics) - Roy Featherstone and David Orin: https://link-springer-com.proxy.library.nd.edu/content/pdf/10.1007/978-3-540-30301-5_3.pdf
- Modern Robotics: Mechanics, Planning, and Control - Kevin M. Lynch and Frank C. Park: http://hades.mech.northwestern.edu/images/7/7f/MR.pdf
- Underactuated Robotics - Russ Tedrake: http://underactuated.csail.mit.edu/

Resources (some of them free…):

- ETH Robot Dynamics Lecture Notes: https://ethz.ch/content/dam/ethz/special-interest/mavt/robotics-n-intelligent-systems/rsl-dam/documents/RobotDynamics2017/RD_HS2017script.pdf

2 Part:

- Sebastien gros: Numerical optimization course: https://www.youtube.com/playlist?list=PLc2vvxBHfBcrzR8fhWc7qjT1lr51Kjue2
- Convex Optimization - Stephen P. Boyd and Lieven Vandenberghe

https://web.stanford.edu/~boyd/cvxbook/bv_cvxbook.pdf

- Numerical Optimization - Jorge Nocedal and Stephen Wright:

https://link-springer-com.proxy.library.nd.edu/book/10.1007/978-0-387-40065-5

SLIDE NOTATION

$\oplus$ Advantage / pros

$\ominus$ Disadvantage / cons

$\triangleq$ Definition

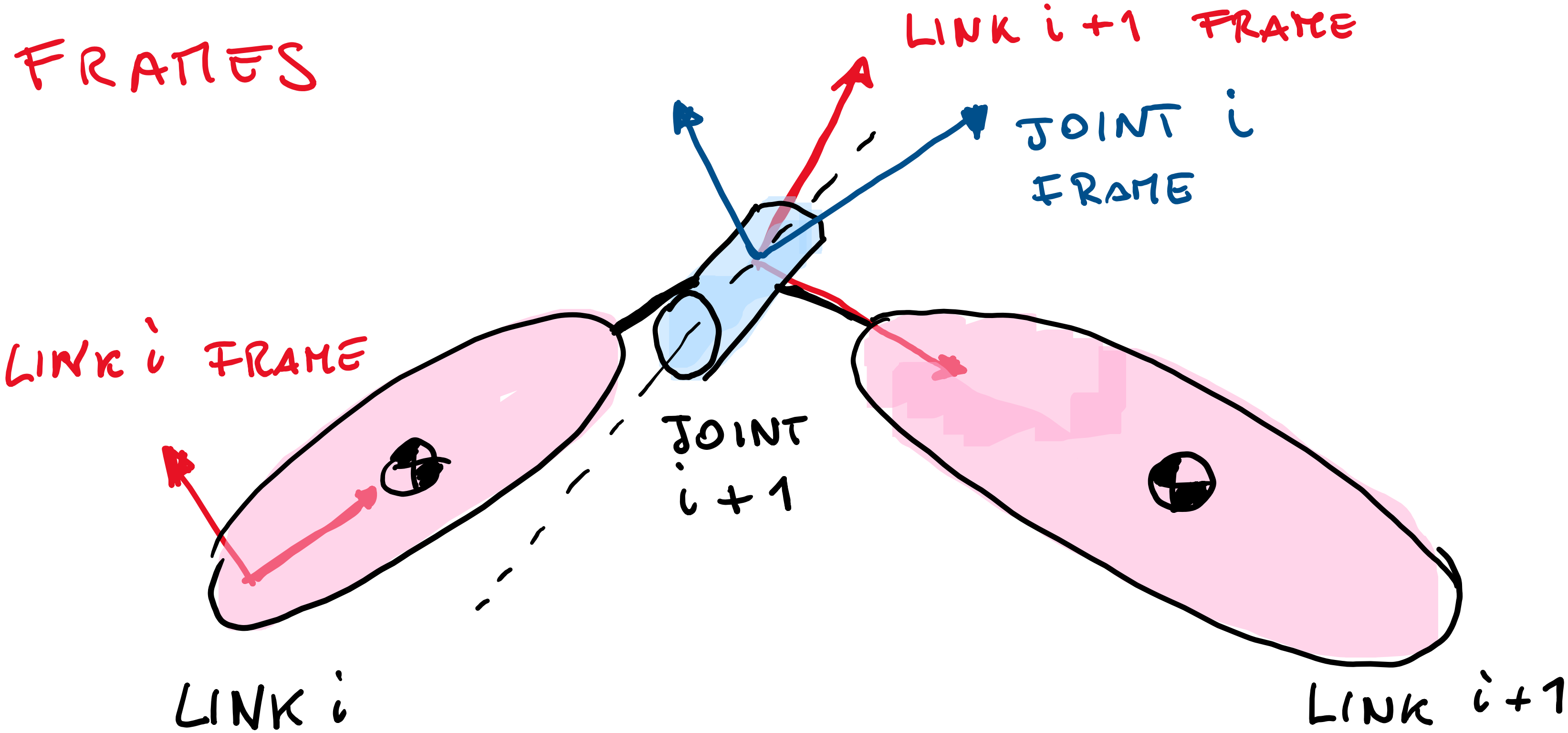
[PRATT 18] local reference to paper

$\odot$ optional slide, for in-depth study, normally hidden during class, not part of the exam

MATH NOTATION

- $I_{3\times3}$: identity matrix 3×3
- $[a]_\times$: skew symmetric matrix (3×3) associated with the cross product $a\,\times$
- Frame : origin + orientation frame
- ${}_W P$: coordinate of point p wrt frame W
- ${}_W R_B$: Rotation matrix $\in SO(3)$ transforming a 3D vector expressed in frame B into frame W
- ${}_W P_{A,B}$: position of point B wrt A expressed in W
- ${}_W I_i$: inertia of body i expressed in the frame W
- wrench : generic 6D force
- ${}_W H_B$: $\begin{bmatrix} {}_W R_B & {}_W O_B \\ 0_{1\times3} & 1 \end{bmatrix}$ position / orientation of frame B w.r.t frame W

FRAMES



LINK FRAME: moves with the link and has origin coincident with the supporting joint

JOINT FRAME: z axis = rotation axis (revolute joints). Pose specified with RIGID Tranform w.r.t the predecessor link