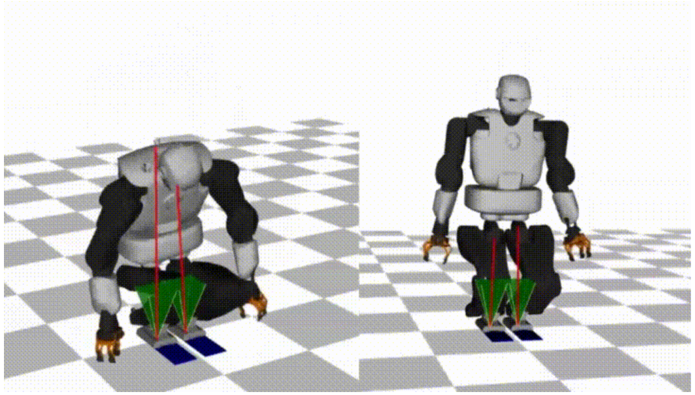
Highly-Dynamic Movements of a Humanoid Robot Using Whole-Body Trajectory Optimization

Master Thesis Presentation
Julian Eßer

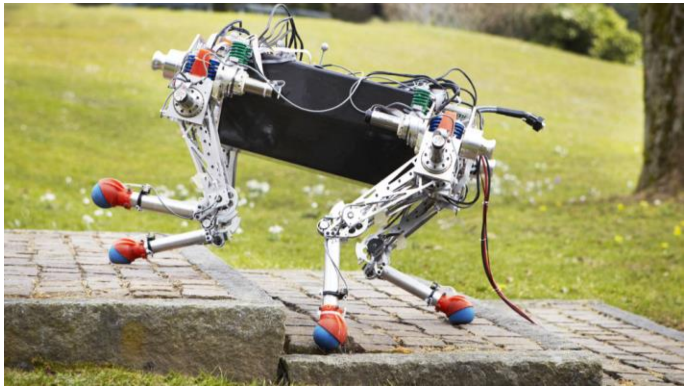
Time: Apr – Sep 2020
Supervisors: Prof. Kirchner, Dr. Bruckmann (UDE)
Mentors: Dr. Kumar, Dr. Stasse (LAAS-CNRS), Dr. Mastalli (Univ. of Edinburgh)



https://github.com/loco-3d/crocoddyl

OUTLINE

- Why Legged Robots? [1]
  - Improved mobility
  - Step over obstacles
  - Adapt to environment



https://rsl.ethz.ch/robots-media/starleth/pictures.html

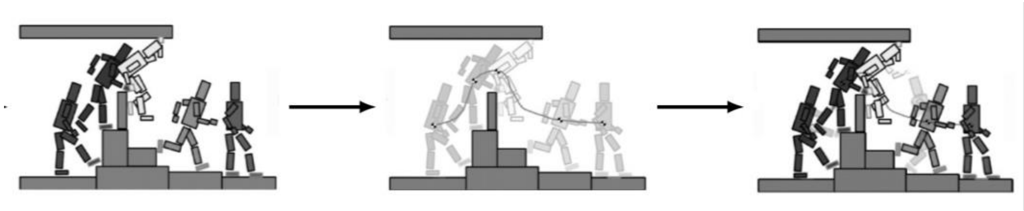
- Why Humanoid Robots? [2]
  - Inspired by human capabilities
  - Human-tailored environments
  - Intuitive collaboration

https://robotik.dfki-bremen.de/en/research/projects/transfit.html

- **Characteristic**: Decoupled Base and Multibody Dynamics

- Reasons for **Complexity**
  - High-dimensional systems
  - Trivial underactuation
  - Nonlinear, hybrid dynamics

- **Decomposition** of Motion Planning into Subproblems



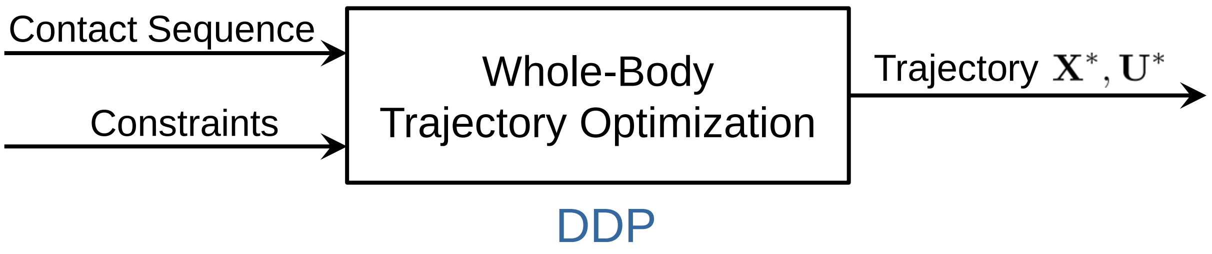
[3]

- **Optimization**-Based Planning for Efficient Motions

- **Goal**: Compute Optimal Trajectories
  - Minimize a given cost function
  - Satisfy a set of constraints
- Classes of **TO Algorithms**
  - Direct methods (e.g. SQP): constrained but slow
  - Indirect methods (e.g DDP): fast but unconstrained
- **Usage** for Legged Locomotion Planning
  - TO based on reduced centroidal dynamics
  - Whole-body TO for efficient motions

- **Goal**: Generate Balanced and Efficient Motion Plans

- **Approach**: DDP-Based Whole-Body TO



- **Contributions** of this Thesis**:**
  - **C1:** Contact Stability Constrained DDP
  - **C2:** Experimental pipeline for whole-body TO
  - **C3:** Physical limitations of RH5 humanoid

FRAMEWORKS AND ROBOT

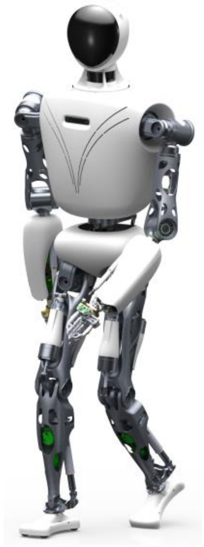
- Involved Frameworks

crocoddyl
Contact Robot Optimal Control by Differential Dynamic Library
https://github.com/loco-3d/crocoddyl
(Optimal Control)

Pinocchio
Efficient and versatile rigid body dynamics algorithms
https://github.com/stack-of-tasks/pinocchio
(Robot Dynamics)

HyRoDyn
https://robotik.dfki-bremen.de/en/research/softwaretools/hyrodyn/
(Parallel Mechanisms)

- RH5 Humanoid Robot
  - Biologically inspired (200 cm, 32 DoFs)
  - Lightweight (62 kg)
  - Series-parallel hybrid robot [4]
  - Tree-type robot model


(Quelle: DFKI GmbH)

OUTLINE

1. Introduction
2. Contact Stability Constrained DDP
3. Application to a Humanoid Robot
   - Bipedal Walking Variants
   - Highly-Dynamic Movements
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DDP FORMULATION

- Finite Horizon Optimal Control Problem [5]

$$\boldsymbol{X}^*, \boldsymbol{U}^* = \arg\min_{\mathbf{X},\mathbf{U}} l_N(x_N) + \sum_{k=0}^{N-1} \int_{t_k}^{t_k+\Delta t} l_k(\mathbf{x}, \mathbf{u}) dt$$

- Cost at One Knot of the OC Problem

$$l_k = \sum_{c=1}^{C} \alpha_c \Phi_c(\boldsymbol{q}, \dot{\boldsymbol{q}}, \boldsymbol{\tau})$$

- Multi-Contact Dynamics as Holonomic Constraints [6]

$$\begin{bmatrix} \dot{\mathbf{v}} \\ -\boldsymbol{\lambda} \end{bmatrix} = \begin{bmatrix} \mathbf{M} & \mathbf{J}_c^\top \\ \mathbf{J}_c & \mathbf{0} \end{bmatrix}^{-1} \begin{bmatrix} \boldsymbol{\tau}_b \\ -\mathbf{a_0} \end{bmatrix}$$

$$\mathbf{J}_c = \frac{\delta \phi}{\delta \mathbf{q}}, \quad \phi(\mathbf{q}) = 0$$

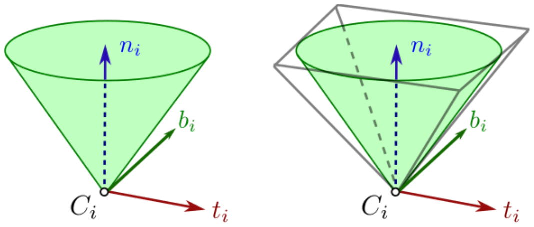
CONTACT STABILITY CONSTRAINED DDP

- **Idea**: Constrain Contact Stability for Each Contact

- **Conditions** for Contact Stability [7]
  I. Unilaterality of the forces
  II. Forces inside friction cone
  III. Center of Pressure (CoP) inside contact area

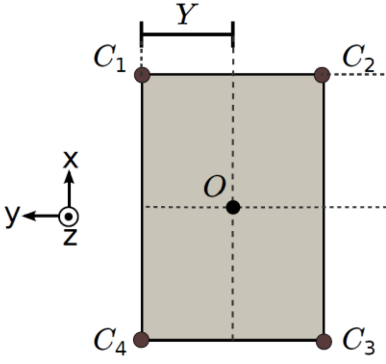
- **Constraints** for Unilaterality (I) and Friction Cone (II)

$$f_i^z > 0$$
$$| f_i^x | \leq \mu f_i^z$$
$$| f_i^y | \leq \mu f_i^z$$



https://scaron.info/teaching/friction-cones.html

- CoP Stability Conditions



[7]

$$-X \leq C_x \leq X$$
$$-Y \leq C_y \leq Y$$

- CoP Computation

$$\boldsymbol{p}_{CoP} = \frac{\boldsymbol{n} \times \boldsymbol{\tau}_O^c}{\boldsymbol{f}^c \cdot \boldsymbol{n}}$$

- **Constraints** for CoP (III)

$$\underbrace{\begin{bmatrix} Xn_0 & Xn_1 & Xn_2 & 0 & -n_2 & n_1 \\ Xn_0 & Xn_1 & Xn_2 & 0 & n_2 & -n_1 \\ Yn_0 & Yn_1 & Yn_2 & n_2 & 0 & -n_0 \\ Yn_0 & Yn_1 & Yn_2 & -n_2 & 0 & n_0 \end{bmatrix}}_{\text{A}} \underbrace{\begin{bmatrix} f^x \\ f^y \\ f^z \\ \tau^x \\ \tau^y \\ \tau^z \end{bmatrix}}_{\text{w}} \geq \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

INTEGRATION INTO CROCODDYL

- **Goal**: Integrate CoP Constraints into a Novel Cost Function

- **Residual** and **Cost** Computation

$$\boldsymbol{r} = \boldsymbol{A}\boldsymbol{w} \geq \boldsymbol{0}$$

$$\Phi_{CoP} = \begin{cases} \frac{1}{2}\boldsymbol{r}^T\boldsymbol{r} & |\ \mathrm{lb} > \boldsymbol{r} > \mathrm{ub} \\ 0 & |\ \mathrm{lb} \leq \boldsymbol{r} \leq \mathrm{ub} \end{cases}$$

(Outside contact area)

(Inside contact area)

$$\mathrm{lb} = \boldsymbol{0}, \mathrm{ub} = \boldsymbol{\infty}$$

- Analytical Computation of **Derivatives**

OUTLINE

FORMULATION OF THE OPTIMIZATION

- Robot **Tasks**

$$\Phi_{\text{foot}} = \| \boldsymbol{f}(t) - \boldsymbol{f}^{\text{ref}}(t) \|_2^2$$

$$\Phi_{\text{CoM}} = \| \boldsymbol{c}(t) - \boldsymbol{c}^{\text{ref}}(t) \|_2^2$$

- Inequality Constraints for **Physical Consistency**

$$\boxed{l_k = \sum_{c=1}^{C} \alpha_c \Phi_c(\boldsymbol{q}, \dot{\boldsymbol{q}}, \boldsymbol{\tau})}$$

$$\Phi_{\text{CoP}}, \Phi_{\text{friction}}, \Phi_{\text{joints}} = \begin{cases} \frac{1}{2}\boldsymbol{r}^T\boldsymbol{r} & \mid \text{lb} > \boldsymbol{r} > \text{ub} \\ 0 & \mid \text{lb} \leq \boldsymbol{r} \leq \text{ub} \end{cases}$$

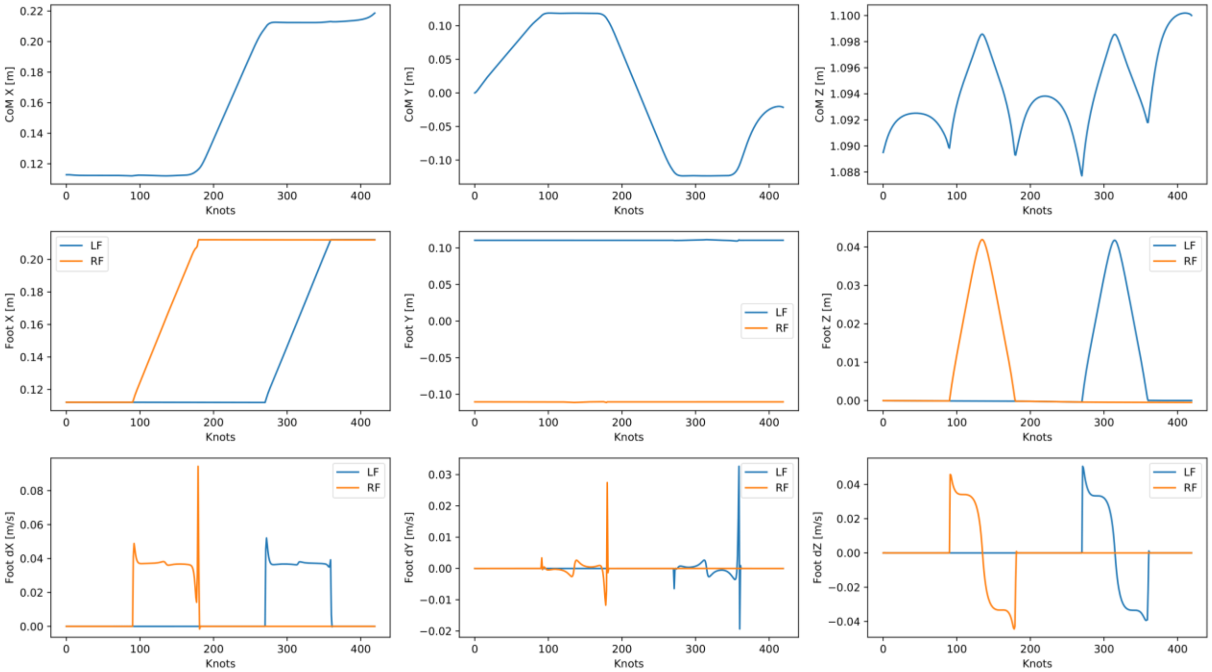
- Further **Regularization** Terms

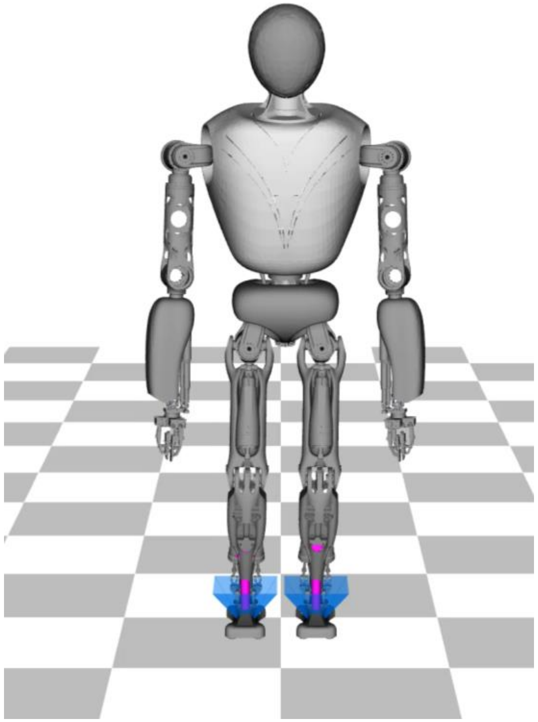
$$\Phi_{\text{torque}} = \| \boldsymbol{\tau}(t) \|_2^2$$

$$\Phi_{\text{posture}} = \| \boldsymbol{q}(t) - \boldsymbol{q}^{\text{ref}}(t) \|_2^2$$

Gait Characteristics		Optimization Constraints	
Step length:	10 cm	Tasks:	$\Phi_{\text{foot}}, \Phi_{\text{CoM}}$
Step height:	5 cm	Stability:	Φ_{friction}
Time:	12 s	Limits:	Φ_{joint}, torques
Step size:	0.03 s	Regularization:	$\Phi_{\text{posture}}, \Phi_{\text{torque}}$

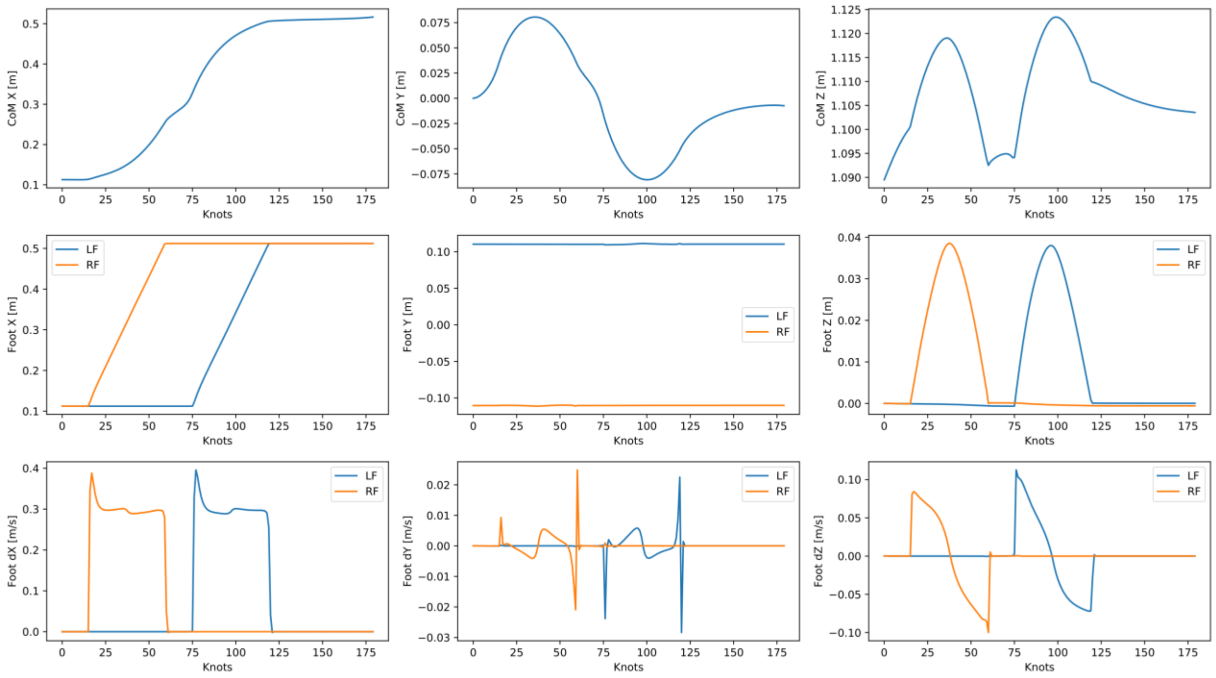
- Static Stability Criterion

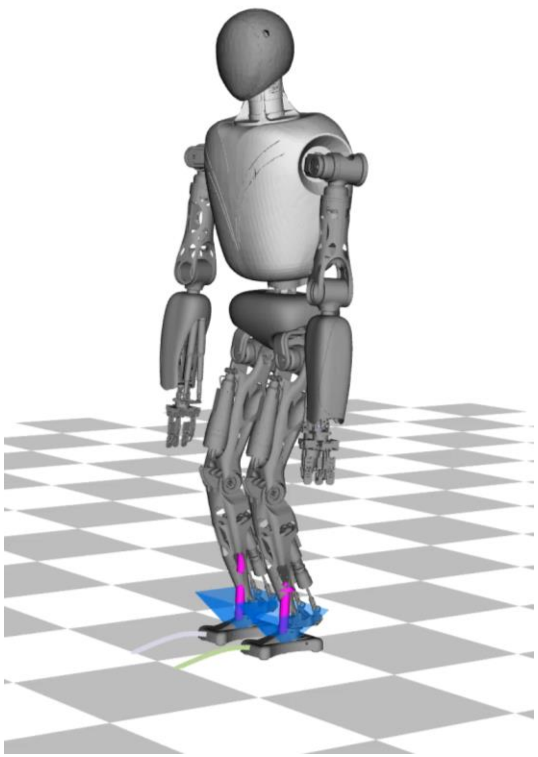




Gait Characteristics		Optimization Constraints	
Step length:	40 cm	Tasks:	Φ_{foot}
Step height:	5 cm	Stability:	Φ_{CoP}, Φ_{friction}
Time:	2 s/step	Limits:	Φ_{joint}, torques
Step size:	0.03 s	Regularization:	Φ_{posture}, Φ_{torque}

- Contact Stability Constrained DDP

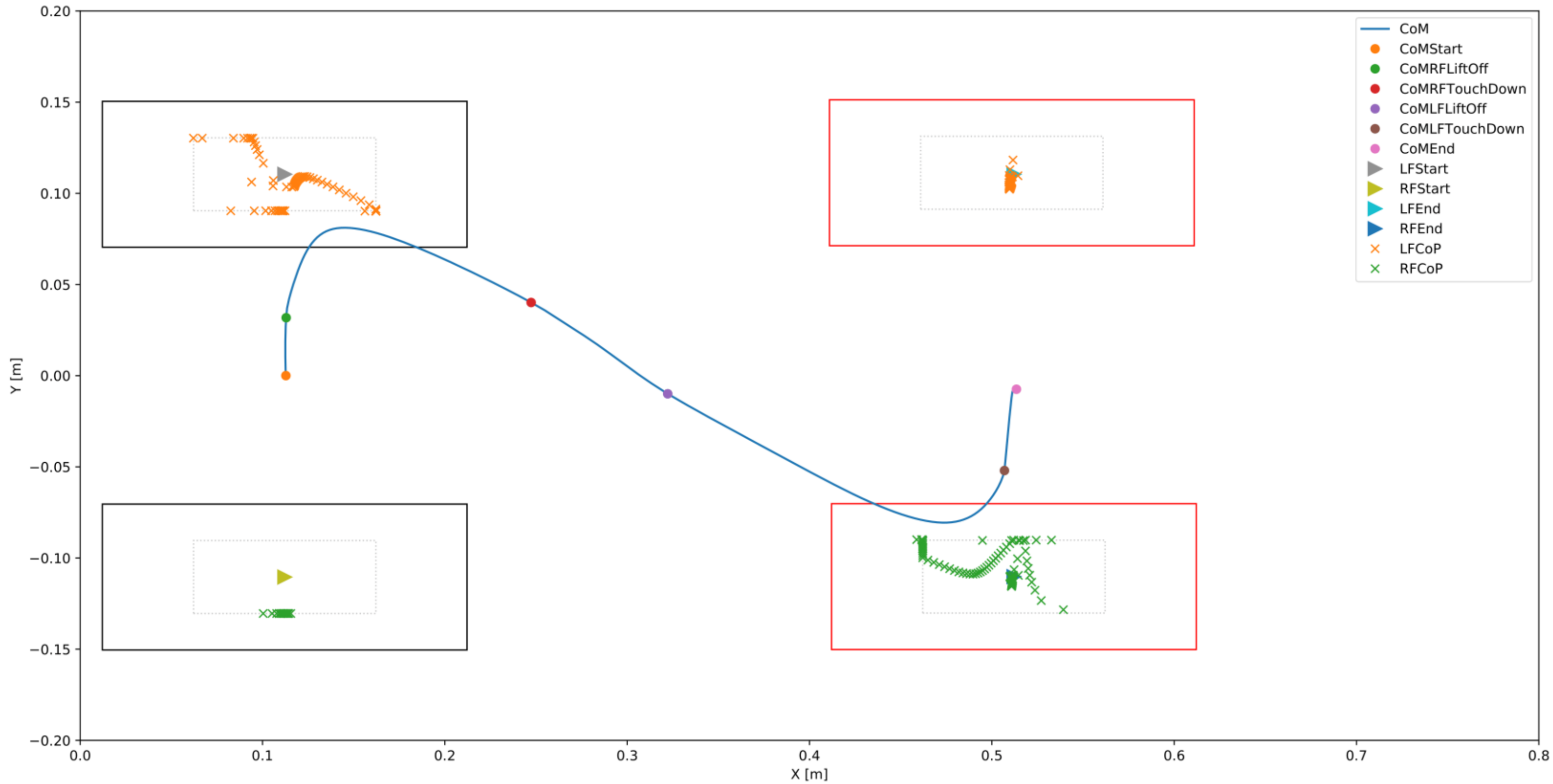




EVALUATION OF CONTACT STABILITY

- Stability Analysis for Dynamic Walking

(50% Foot Area)
(100% Foot Area)



- **Finding**: Proposed Approach Yields Balanced Motions

- **Flight Phases**: Physical Consistency of Contact Timings
  - Falling time given by physics
  - Derive other timings

- **Numerical Drift** in the Holonomic Constraints
  - Baumgarte stabilization
  - Reduce integration step size

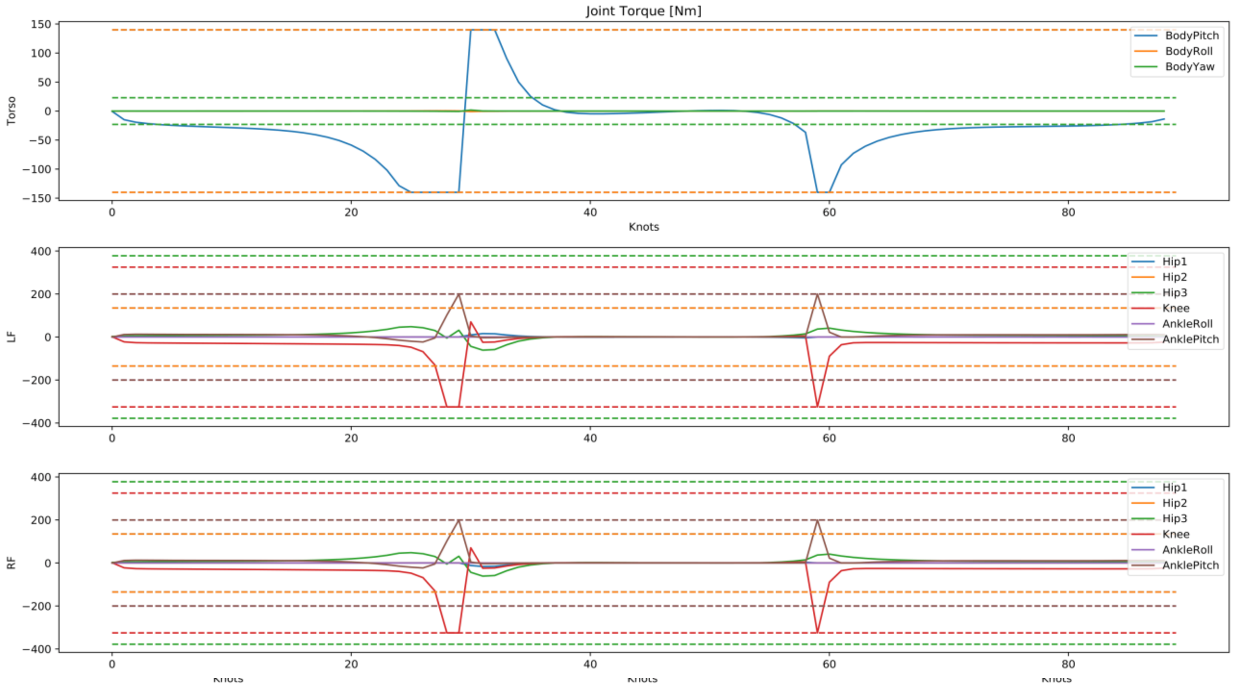
- **Multi-Phase** Optimal Control Problem

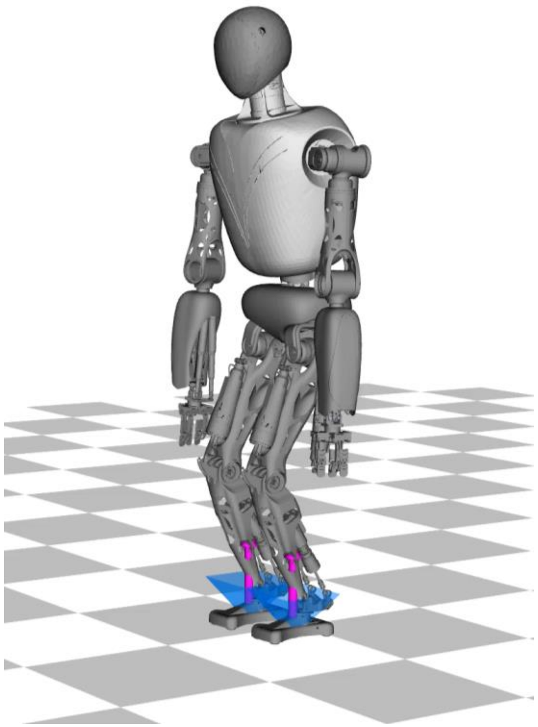
$$\boldsymbol{X}^*, \boldsymbol{U}^* = \arg\min_{\mathbf{X},\mathbf{U}} \sum_{p=0}^{P} \sum_{k=0}^{N} \int_{t_k}^{t_k+\Delta t} l_p(\mathbf{x}, \mathbf{u}) dt$$

RESULTS: VERTICAL JUMP

Jump Characteristics		Optimization Constraints	
Jump length:	0 cm	Tasks:	Φ_{foot}
Jump height:	10 cm	Stability:	$\Phi_{\text{CoP}}, \Phi_{\text{friction}}$
Total time:	0.9 s	Limits:	Torques
Step size:	0.01 s	Regularization:	$\Phi_{\text{posture}}, \Phi_{\text{torque}}$

- Analysis of System Limits

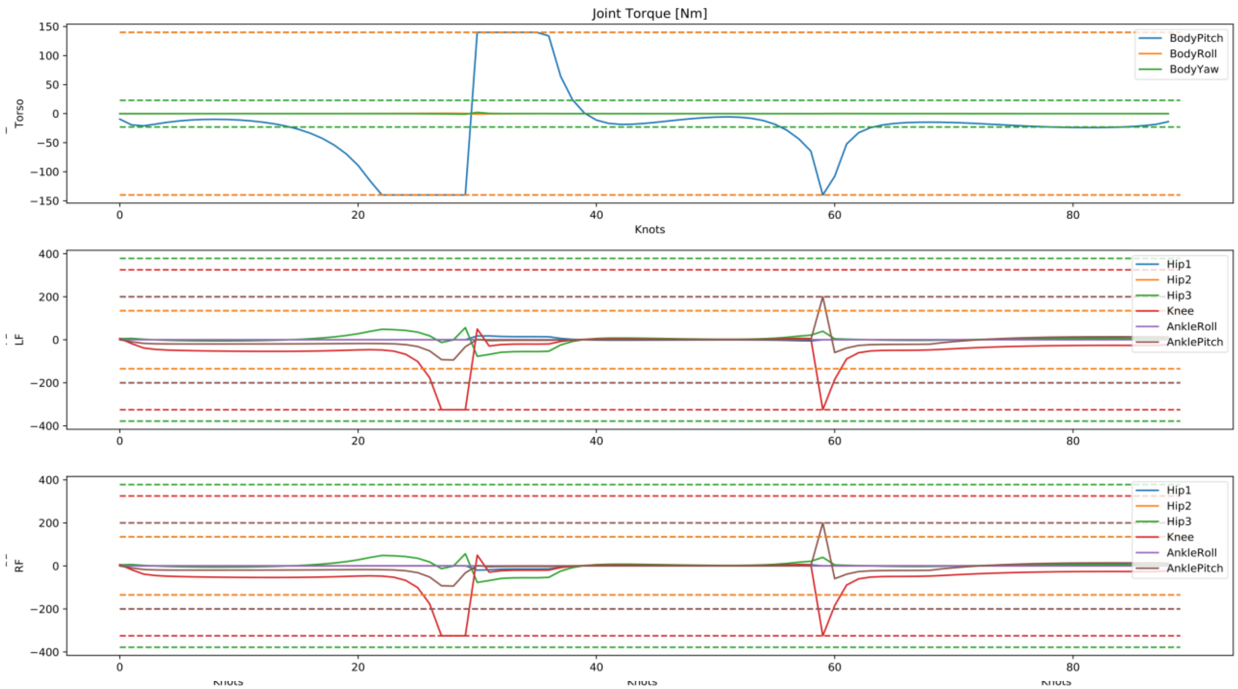


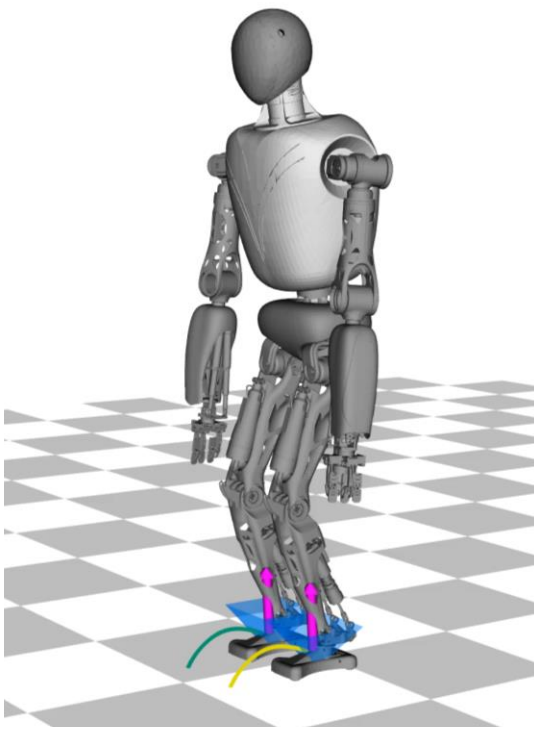


RESULTS: FORWARD JUMP

Jump Characteristics		**Optimization Constraints**	
Jump length:	30 cm	Tasks:	Φ_{foot}
Jump height:	10 cm	Stability:	$\Phi_{\text{CoP}}, \Phi_{\text{friction}}$
Total time:	0.9 s	Limits:	Torques
Step size:	0.01 s	Regularization:	$\Phi_{\text{posture}}, \Phi_{\text{torque}}$

- Analysis of System Limits

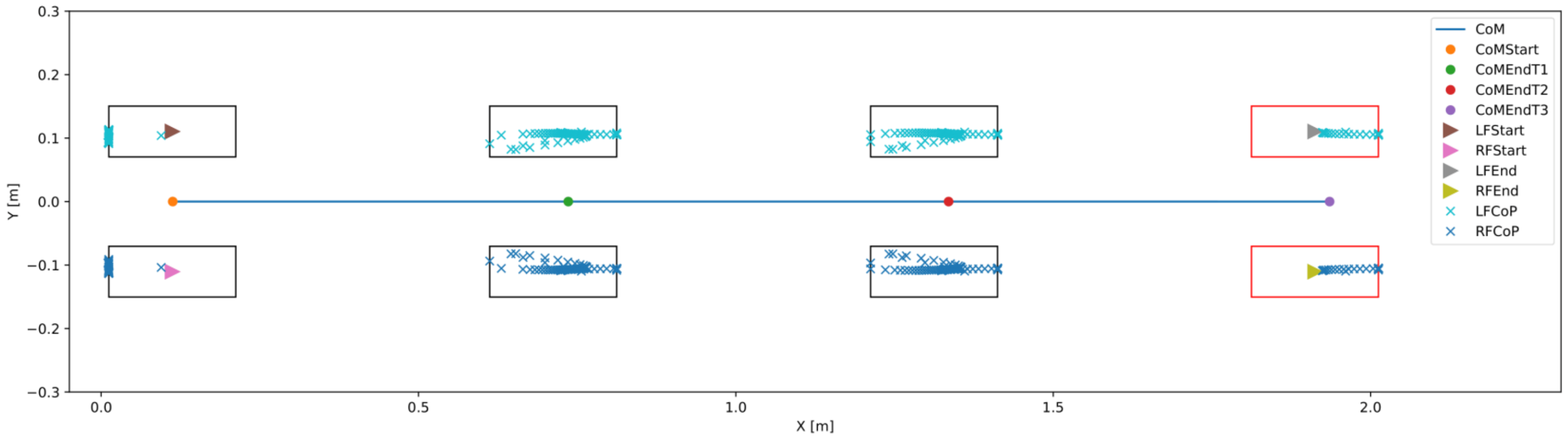


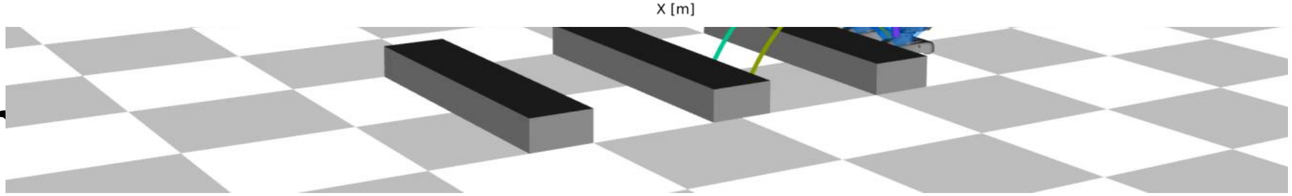


RESULTS: MULTIPLE OBSTACLES JUMPS

Jump Characteristics		Optimization Constraints	
Jump length:	60 cm	Tasks:	Φ_{foot}
Jump height:	25 cm	Stability:	$\Phi_{\text{CoP}}, \Phi_{\text{friction}}$
Total time:	0.9 s / jump	Limits:	-
Step size:	0.01 s	Regularization:	$\Phi_{\text{posture}}, \Phi_{\text{torque}}$

- Stabili





- **Findir**

EVALUATION OF THE SYSTEM DESIGN

- Case Studies of Increasing Complexity

	Position Limits	Torque Limits	Velocity Limits
Vertical Jump ($l = 0$ cm)			
$h = 1$ cm	✓	✓	✓
$h = 5$ cm	✓	✓	$\times_3$
$h = 10$ cm	✓	(✓)	$\times_3$
$h = 20$ cm	✓	(✓)	$\times_5$
$h = 30$ cm	✓	(✓)	$\times_7$
Forward Jump ($h = 10$ cm)			
$l = 10$ cm	✓	(✓)	$\times_7$
$l = 20$ cm	✓	(✓)	$\times_7$
$l = 30$ cm	✓	(✓)	$\times_7$
$l = 40$ cm	✓	(✓)	$\times_7$
$l = 50$ cm	✓	(✓)	$\times_7$
Obstacle Jump ($h = 25$ cm)			
$l = 60$ cm	✓	$\times_5$	$\times_7$

- Critical Joint Velocities: Body, Knee, Hip, Shoulder
- **Result**: Guidelines for Next Design Iteration

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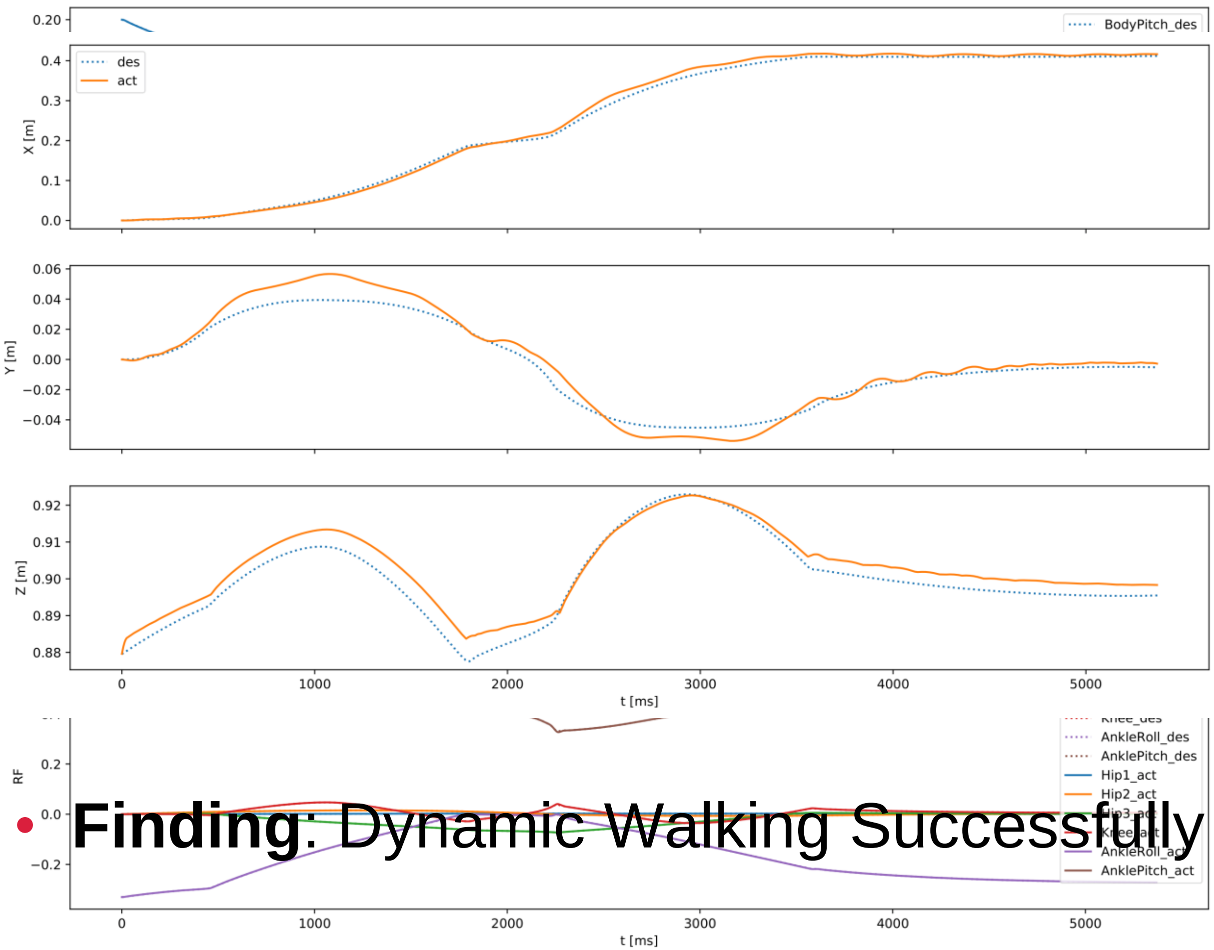
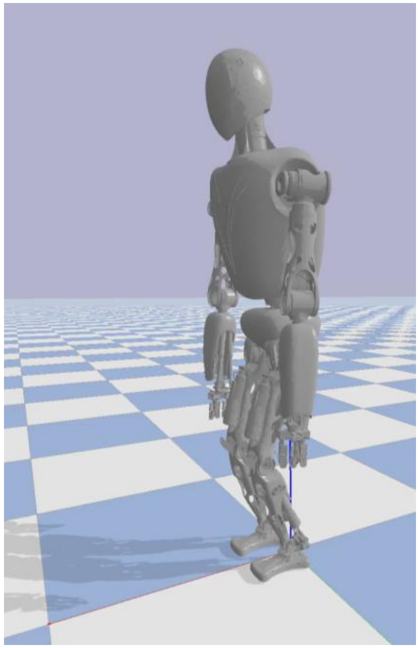
SIMULATION SETUP

- **Goal**: Online Stabilization of Planned Motions
- Real-Time Physics Simulation: **PyBullet**
  - Rigid contact model
  - Collision detection
- **Pipeline** Comparable to Real Robot
  - Trajectory from file
  - Cubic spline interpolation (1 kHz)
- **Control** Architecture
  - Joint space level
  - PD position/velocity control

RESULTS: DYNAMIC WALKING

- Resulting Base Motion (Uncontrolled)
- Tracking Performance in Joint Space

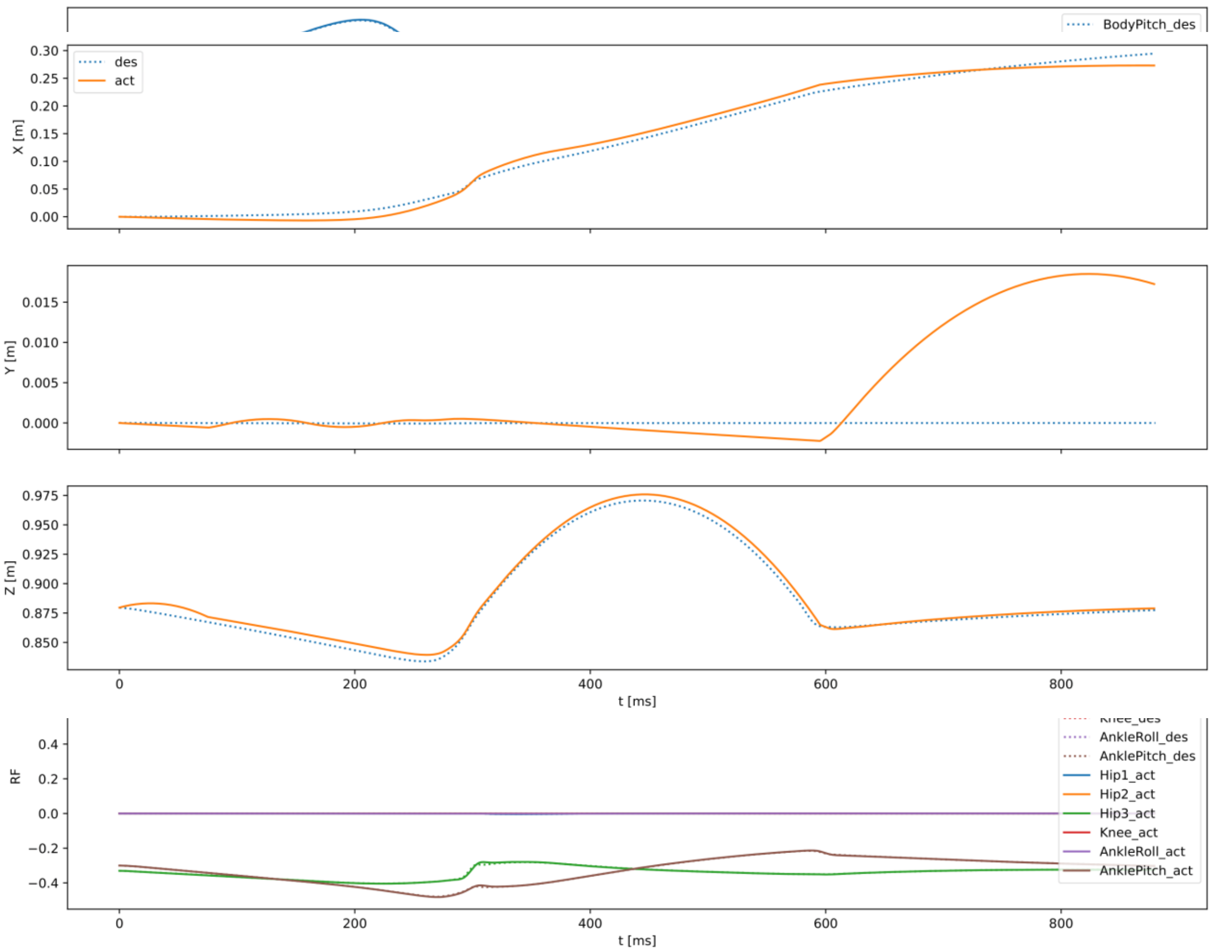


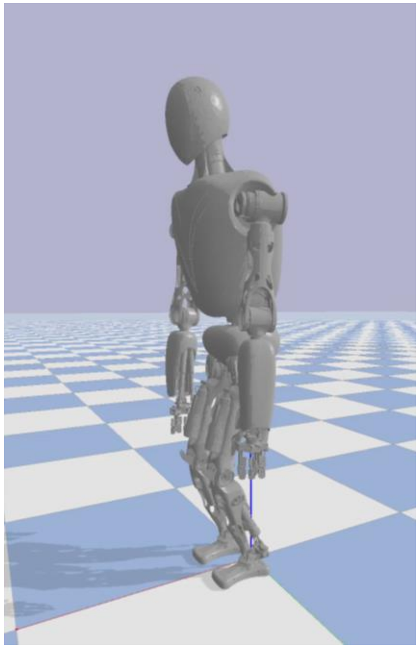


- **Finding**: Dynamic Walking Successfully Stabilized

RESULTS: FORWARD JUMPING

- Resulting Base Motion (Uncontrolled)
  Tracking Performance in Joint Space

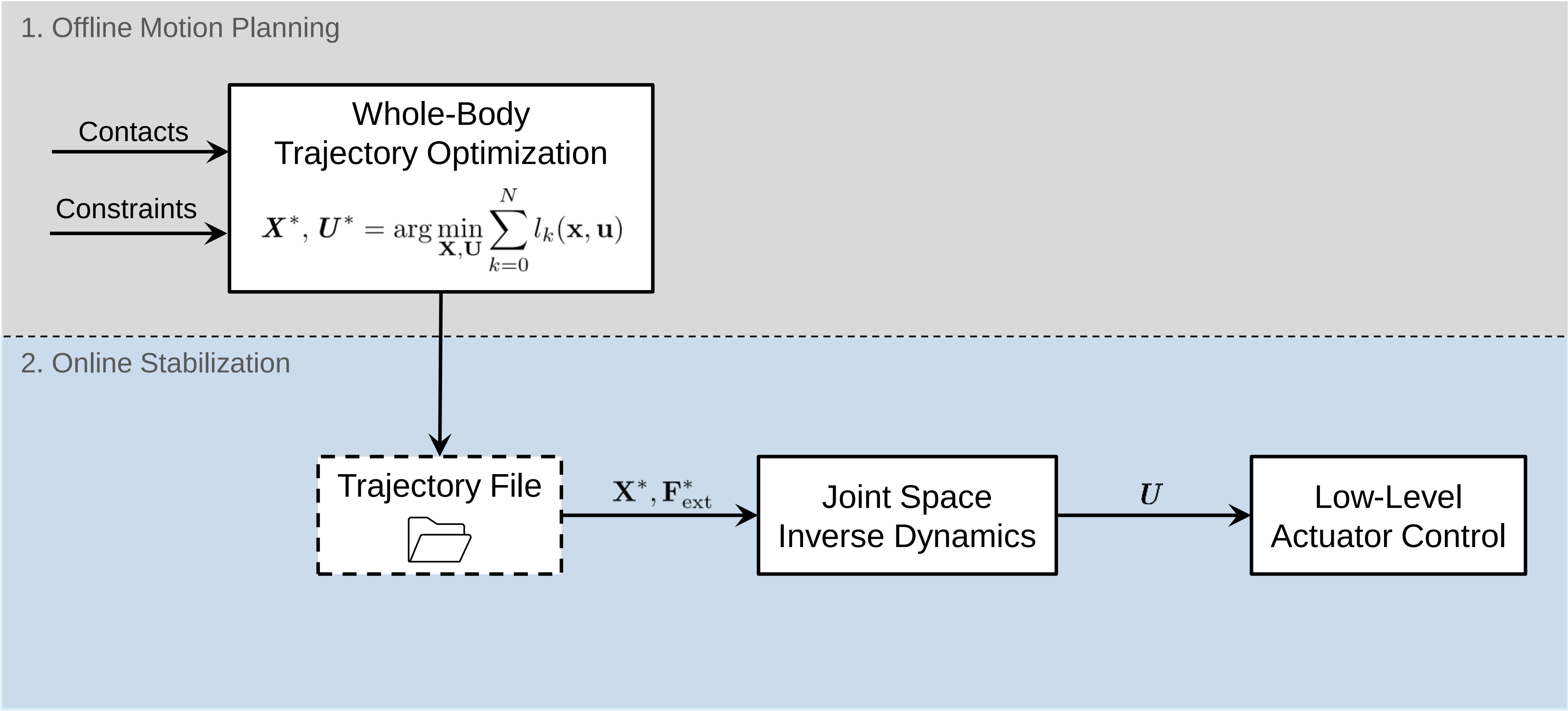




Stabilized

EXPERIMENTAL SETUP

- **Goal**: Online Stabilization of Planned Motions

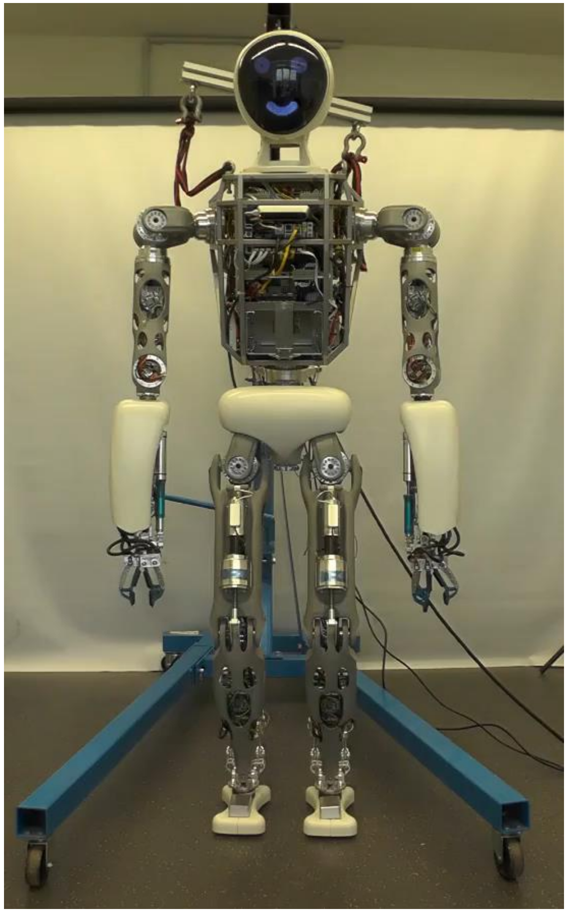


- Four Experiments of Increasing Difficulty

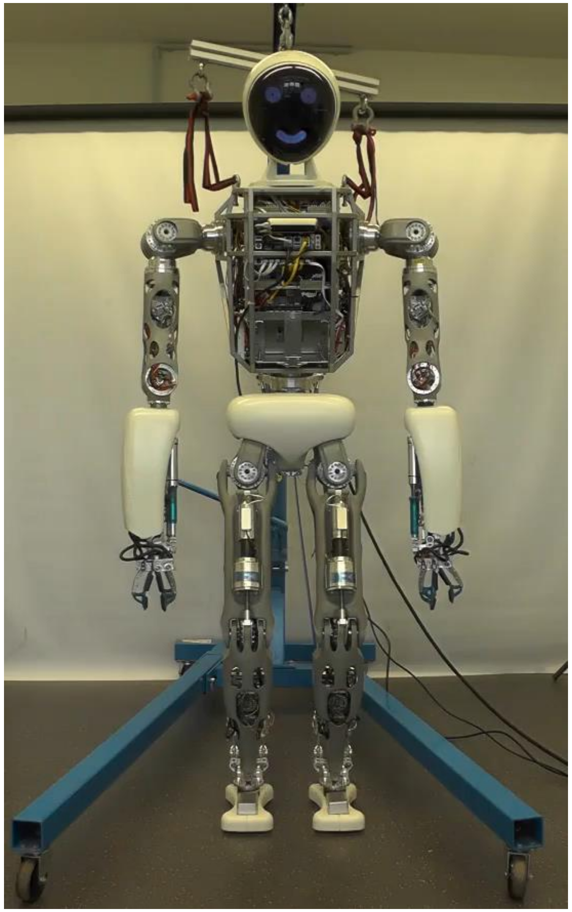
	I Balancing	II Static Walk	III Fast Squats	IV Dynamic Walk
Surface contacts	✓	✓	✓	✓
Base motion	✓	✓	✓	✓
Swing foot motion	✓	✓	✗	✓
Step sequence	✗	✓	✗	✓
Impacts	✗	✓	✗	✓
Dynamic forces	✗	✗	✓	✓
Flight-phases	✗	✗	✗	✗
Success	✓	(✓)	✓	✗

EXPERIMENTS

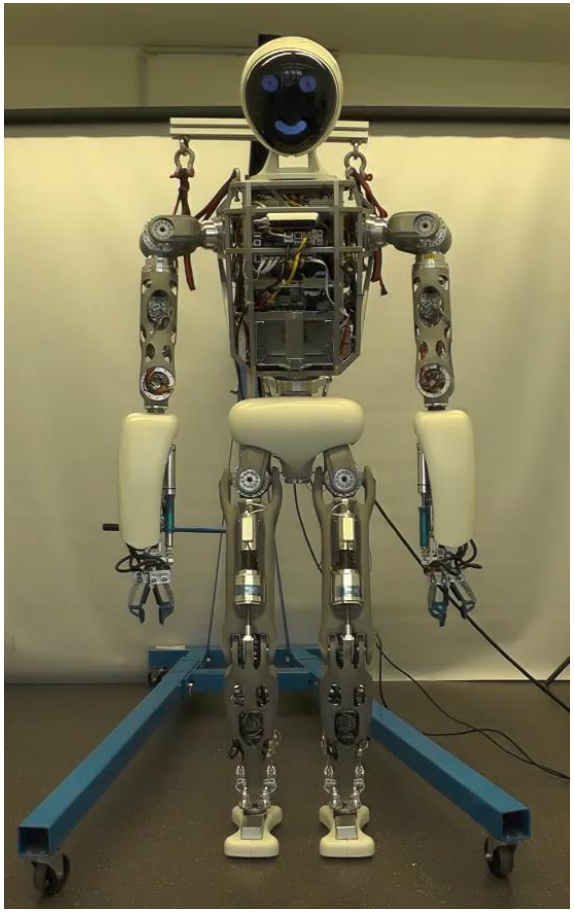
- I: One-Leg Balancing ✓



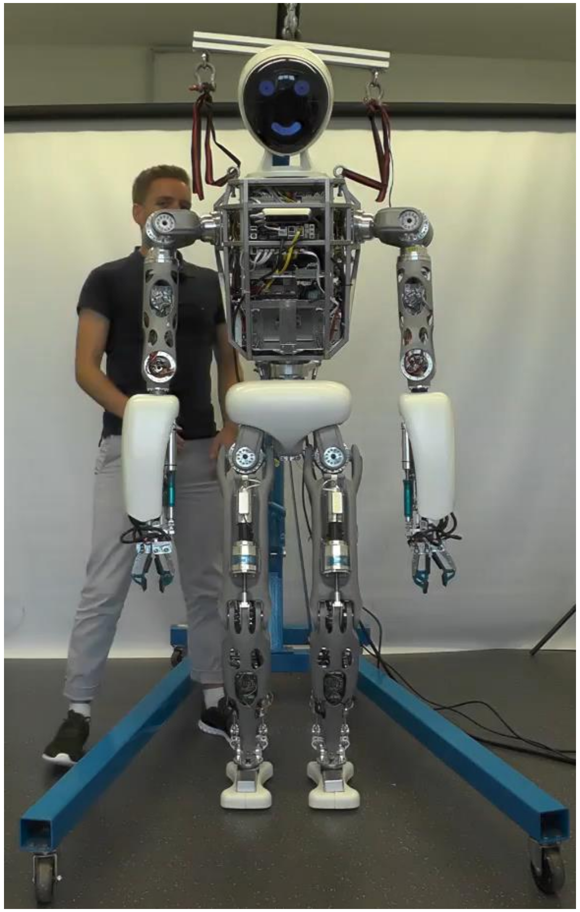
II: Static Walking (✓)



- III: Fast Squats ✓



IV: Dynamic Walking ✗



- **Stability** of the Motions
- Related **Issues**
  - Tracking performance
  - Handling impulses
  - Model discrepancies
  - Mechanical deficiencies
- Actions for **Improvement**
  - Task space control
  - System identification
  - Hardware upgrade

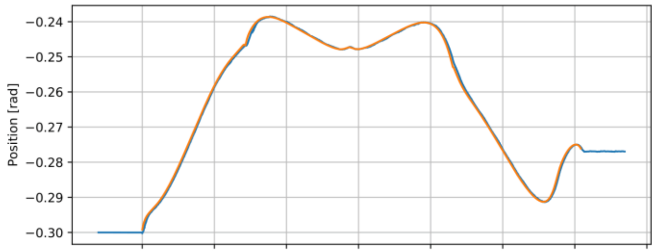


Fig. 1: Ankle Roll Tracking

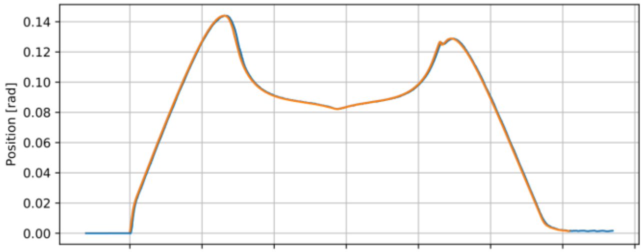


Fig. 2: Ankle Pitch Tracking

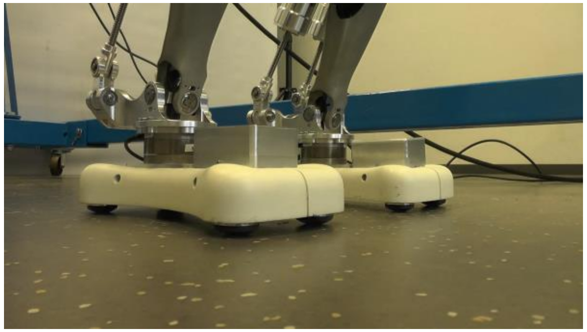
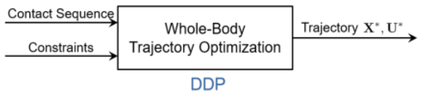


Fig. 3: Deviation in Task Space

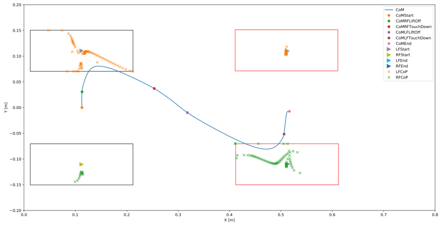
OUTLINE

THESIS SUMMARY

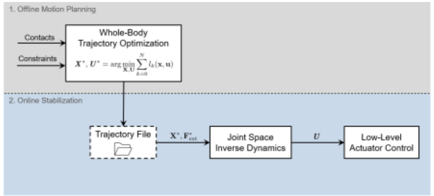
- **Motivation:** Physically Consistent and Efficient Motion Plans
- **Approach:** DDP-Based Whole-Body TO



- **Idea**: Contact Stability Constrained DDP
  - Evaluation: inherently balanced motions
  - Validation: simple control architecture



- **Experimental** Pipeline



- Physical **Limitations** of RH5 Humanoid

	Position Limits	Torque Limits	Velocity Limits
Vertical Jump ($l = 0$ cm)			
$h = 1$ cm	✓	✓	✓
$h = 5$ cm	✓	✓	$\times_3$
$h = 10$ cm	✓	(✓)	$\times_3$
$h = 20$ cm	✓	(✓)	$\times_5$
$h = 30$ cm	✓	(✓)	$\times_7$
Forward Jump ($h = 10$ cm)			
$l = 10$ cm	✓	(✓)	$\times_7$
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$l = 30$ cm	✓	(✓)	$\times_7$
$l = 40$ cm	✓	(✓)	$\times_7$
$l = 50$ cm	✓	(✓)	$\times_7$
Obstacle Jump ($h = 25$ cm)			
$l = 60$ cm	✓	$\times_5$	$\times_7$

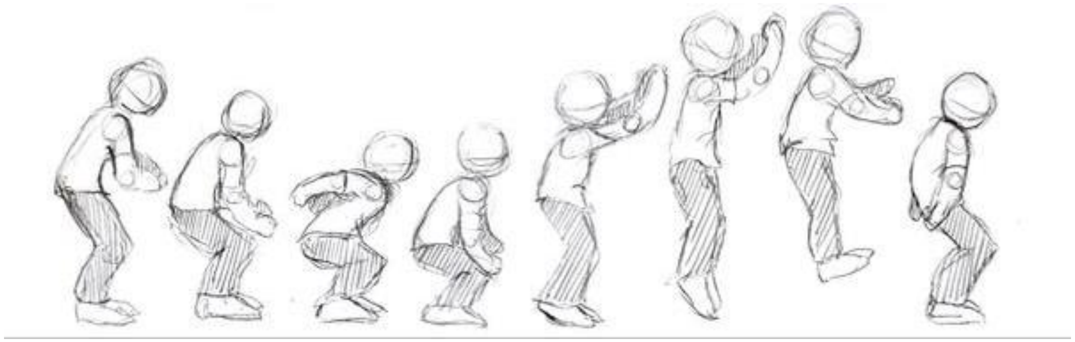
FUTURE DIRECTIONS

- **Assessment**: Large Potential of Whole-Body TO
  - Reduced handcrafted components
  - High-level tasks formulation

1. **Algorithmic** Perspective
   - Inequality constraints embedded in DDP
   - Solving internal closed loops

2. **Control** Perspective
   - Task space control
   - Model predictive control

Thanks for your attention!



https://www.deviantart.com/crystalstarspirit/art/Animation-Jump-Sequence-105385147

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