How Should a Scaffolding Pole-Climbing Robot Look?

Sampling-based parametric design optimisation of a limbed pole-climbing robot

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1. Motivation

Why this application?

- Bring robotic systems in construction to physical-support and manipulation roles, beyond presently common inspection tasks
- Could increase the stagnating productivity in the construction sector

Why climbing?

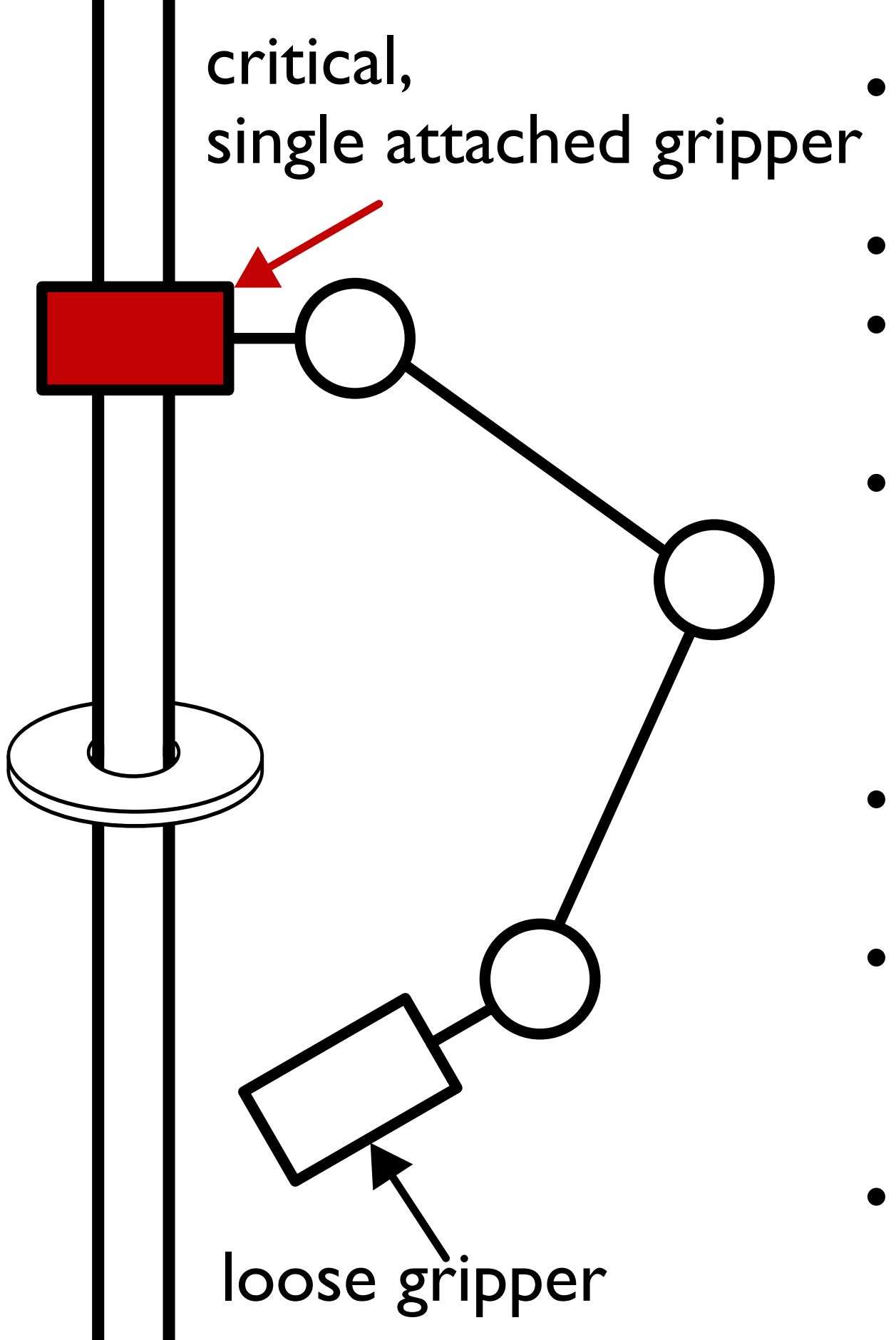
- Requirement: vertical movement
- Possible through different types of locomotion: climbing, flying, or pulling
- Climbing allows load carrying while providing stability

Why scaffolding?

- Scaffolding is employable on the façade of nearly every multi-storey building.
- Scaffolding consists of standardised poles → well-structured environment inside an otherwise unstructured site
- Assembly by robots is possible

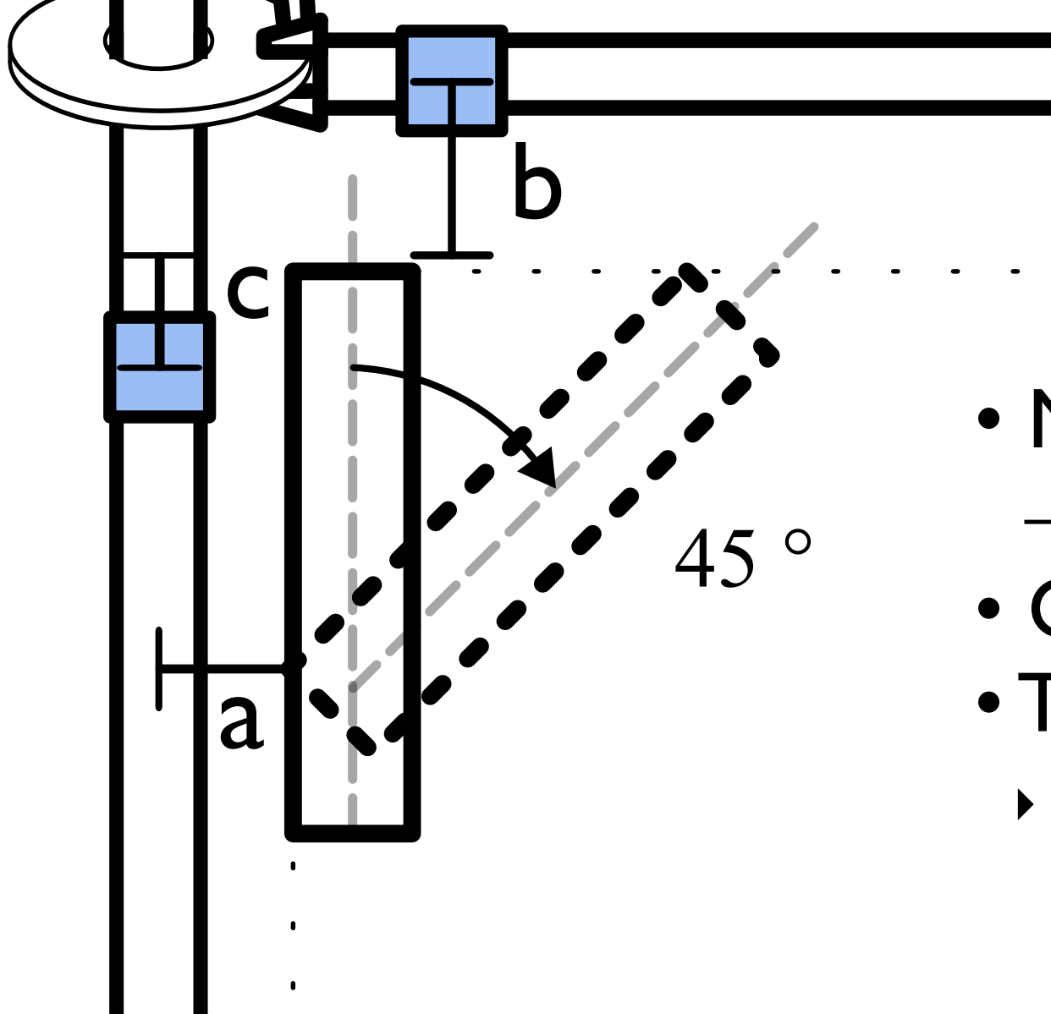
Seville Cathedral

2. Robotic System

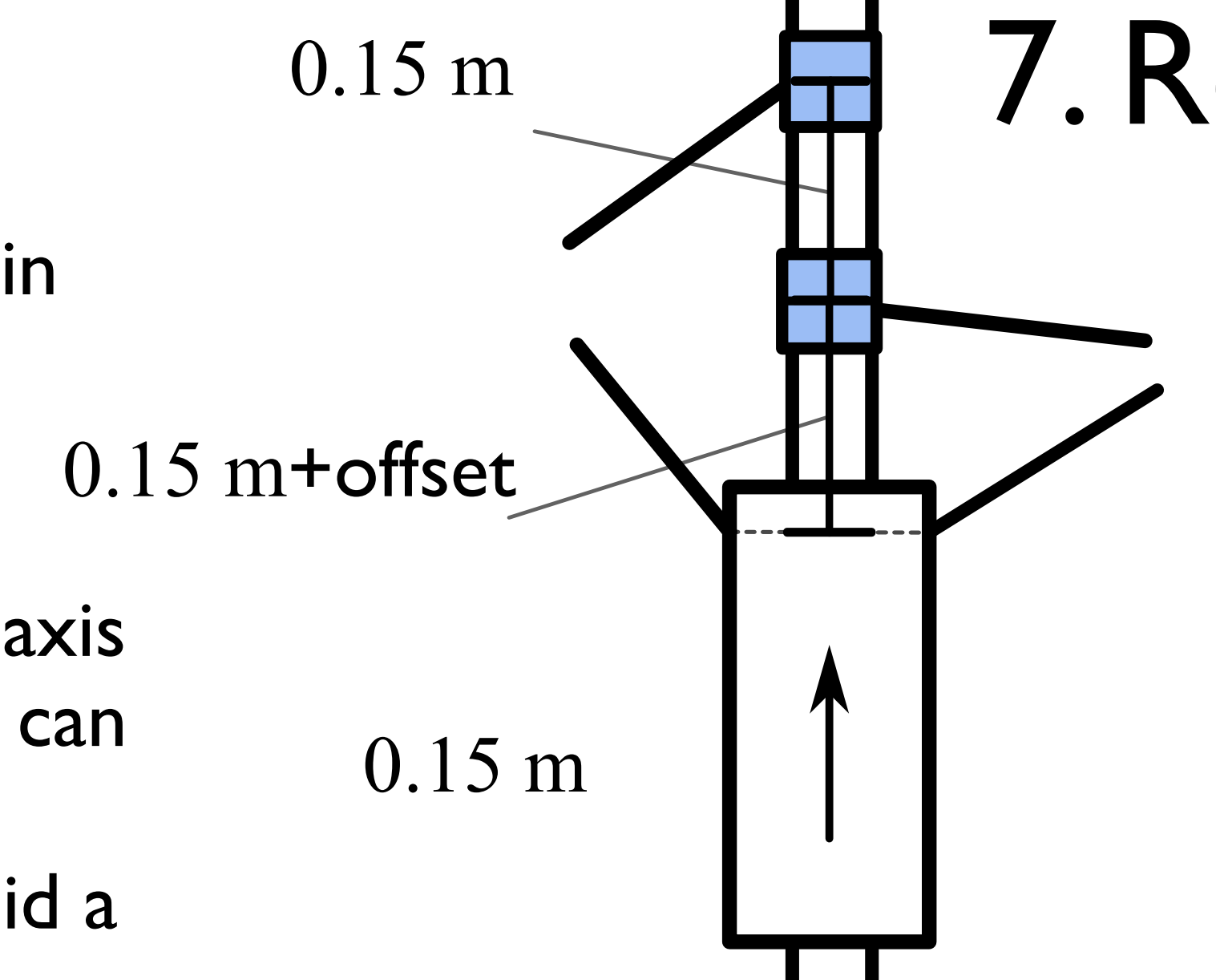


- Scaffolding-based approach frees the climbing robot from the wall's surface properties
- Grippers replace adhesion-based end-effectors
- Base is connected to each gripper by a kinematic chain offering six degrees of freedom or more
- In contrast, wheeled or inchworm systems are challenged with the inherent obstacles of the scaffolding, connecting elements: rosette discs or the perpendicular poles
- The number of limbs is one of the key design considerations
- A two-gripper system will inevitably become a single-gripper system during repositioning → the kinematic chain opens up from a closed one
- A failure of the remaining gripper could be fatal and the lever arm increases
- Modelled as free-floating base and rigid limbs
- A rigid constraint at each end-effector restricts the motion

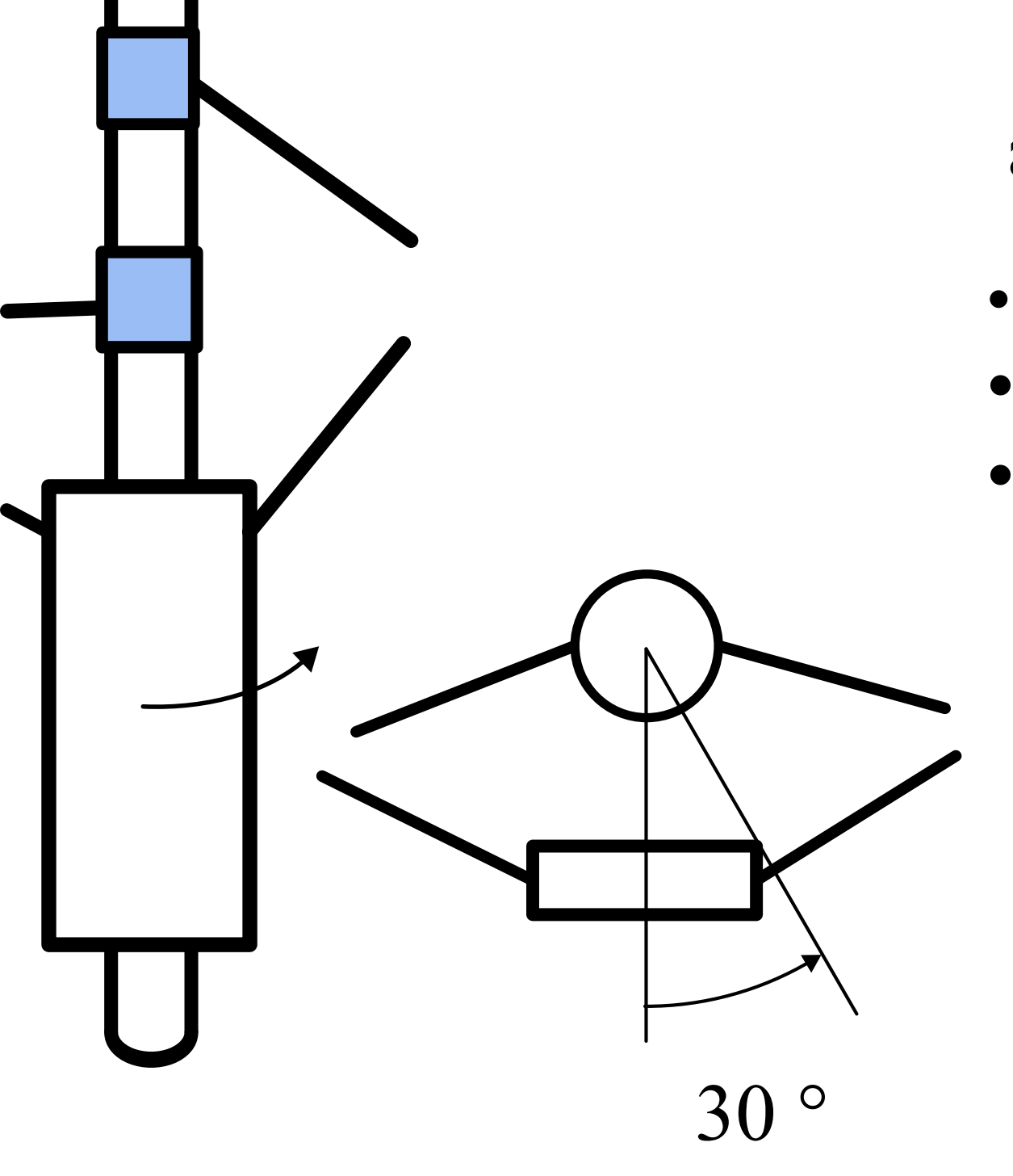
3. Motions



- Minimal subsystem with no open chain → two grippers ensure attachment.
- Obstacle navigation is excluded
- Three key motions:
  - straight-line climbing parallel to the axis of the poles, so that a repetitive gait can be established
  - rotating around the pole axis to avoid a possible pole in the way and allow for navigating
  - switching poles from a vertical to a horizontal one, to allow full climbing of a scaffolding structure



- Target motion trajectory is prescribed for the base
- Fifth-order smoothstep function maps time to the path
- Trajectories are planned free of self- and cross-collisions for the joints using inverse kinematics

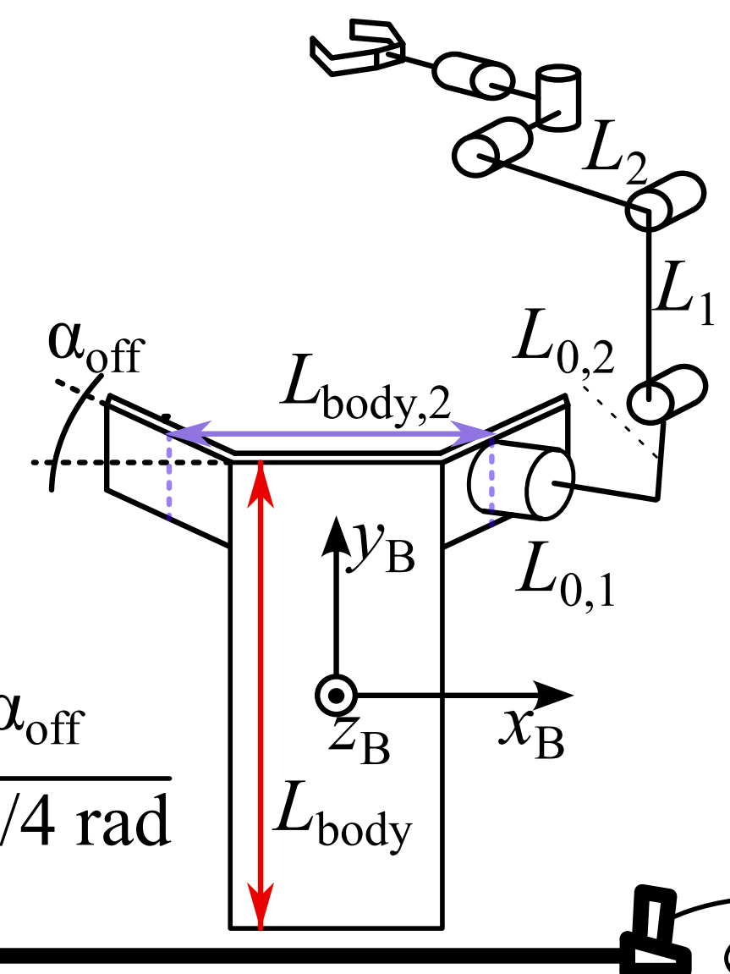


🟦 gripper ▭ base / torso

4. Structural Parameters

- Six parameters are varied, describing the body and the limbs
- A reach requirement of 0.45 m per parameter candidate
- Link inertias, motor placement and mass properties are rebuilt for every candidate

L_1=L_2	$L_{0,1}$	$L_{0,2}$	L_body	$L_{\mathrm{body},2}$	α_off
0.15-0.3 m	0.1-0.3 m	0.08-0.2 m	0.25-0.4 m	0.1-0.3 m	0-π/4 rad

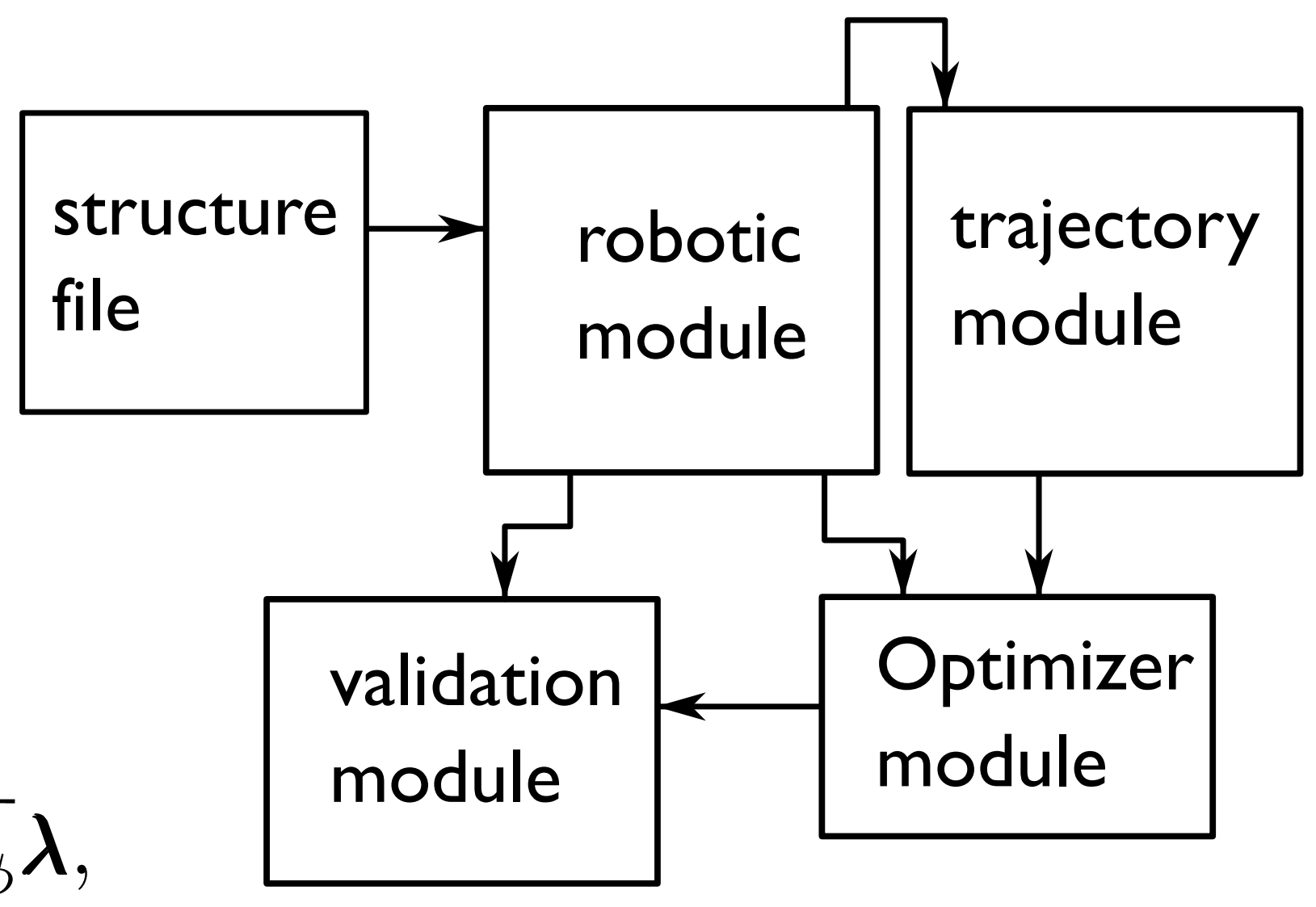


5. Methods

- Torques computed using optimisation at each timestep w.r.t. joint trajectory
- System matrices are constructed symbolically
- Cost function adapted to the task objective

$$\min_{\boldsymbol{\tau},\boldsymbol{\lambda}} \quad \mathcal{L}_\tau$$

$$\text{s.t.} \quad \mathbf{M}\ddot{\mathbf{q}}_\mathrm{d} + \mathbf{C}\dot{\mathbf{q}}_\mathrm{d} + \mathbf{G} = \mathbf{S}^\mathsf{T}\boldsymbol{\tau} + \mathbf{J}_\phi^\mathsf{T}\boldsymbol{\lambda},$$
$$-\hat{t}\mathbf{1} \le \boldsymbol{\tau} \le \hat{t}\mathbf{1}.$$

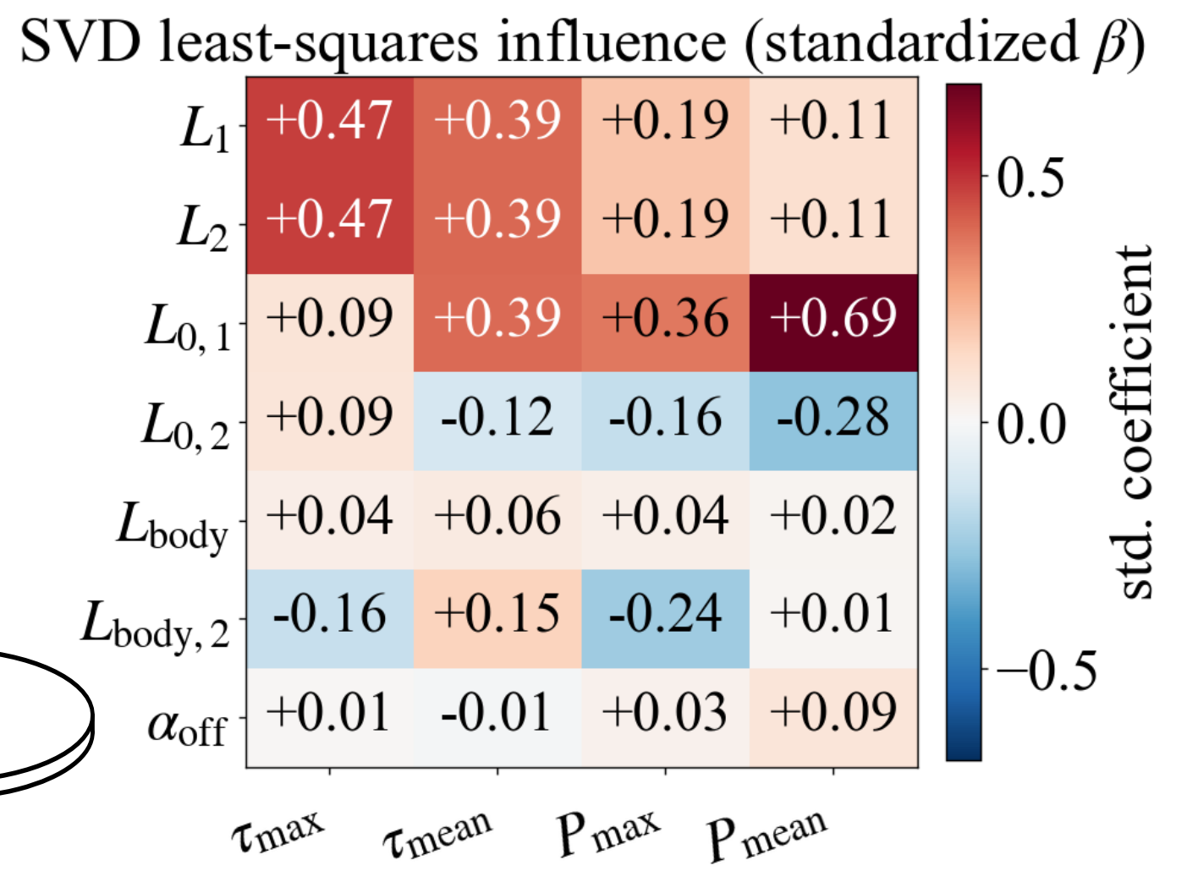


structure file → robotic module → trajectory module → Optimizer module → validation module

6. Numerical Study

Parameter correlation - coarse search

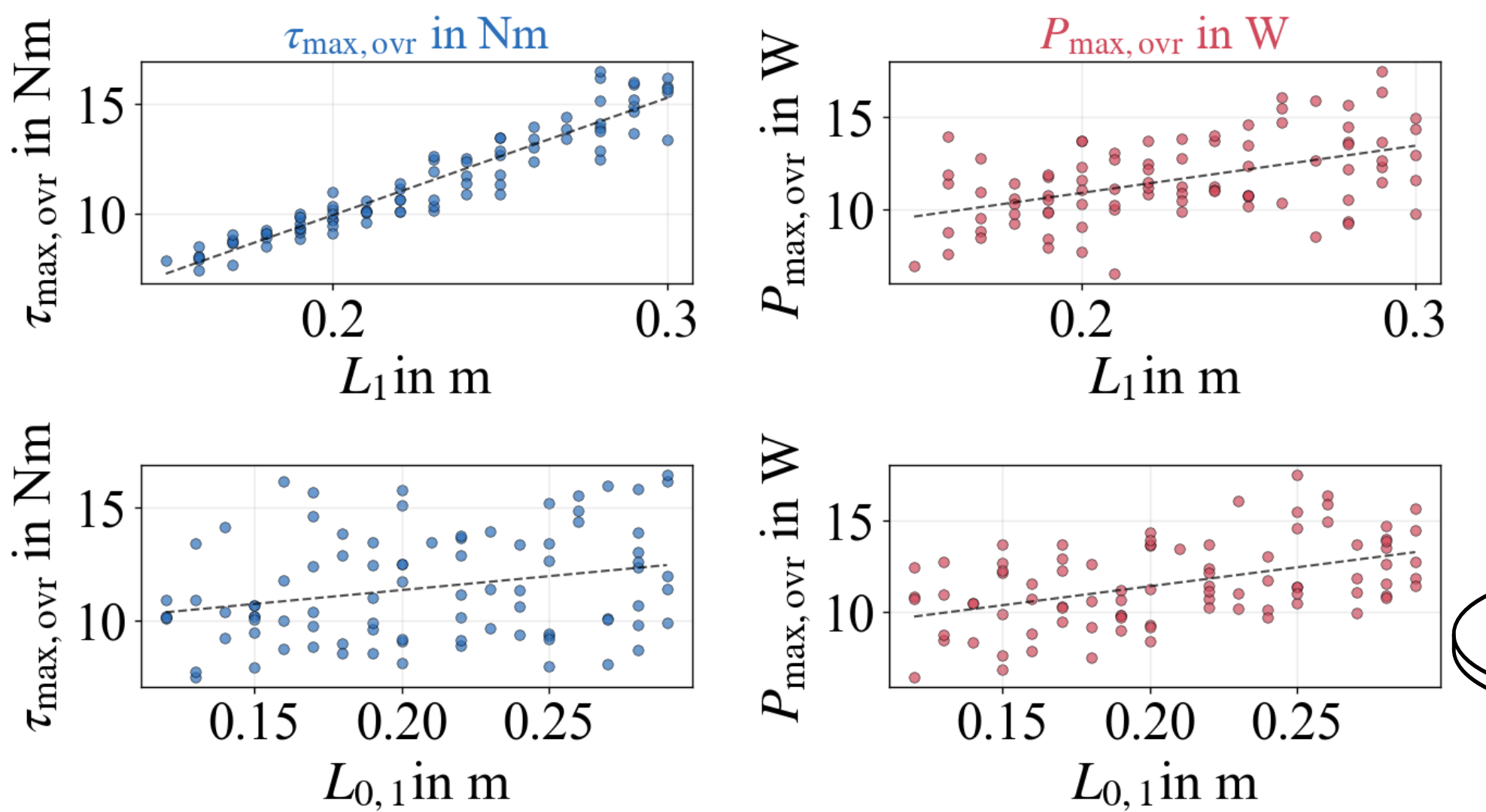
straight-line climbing



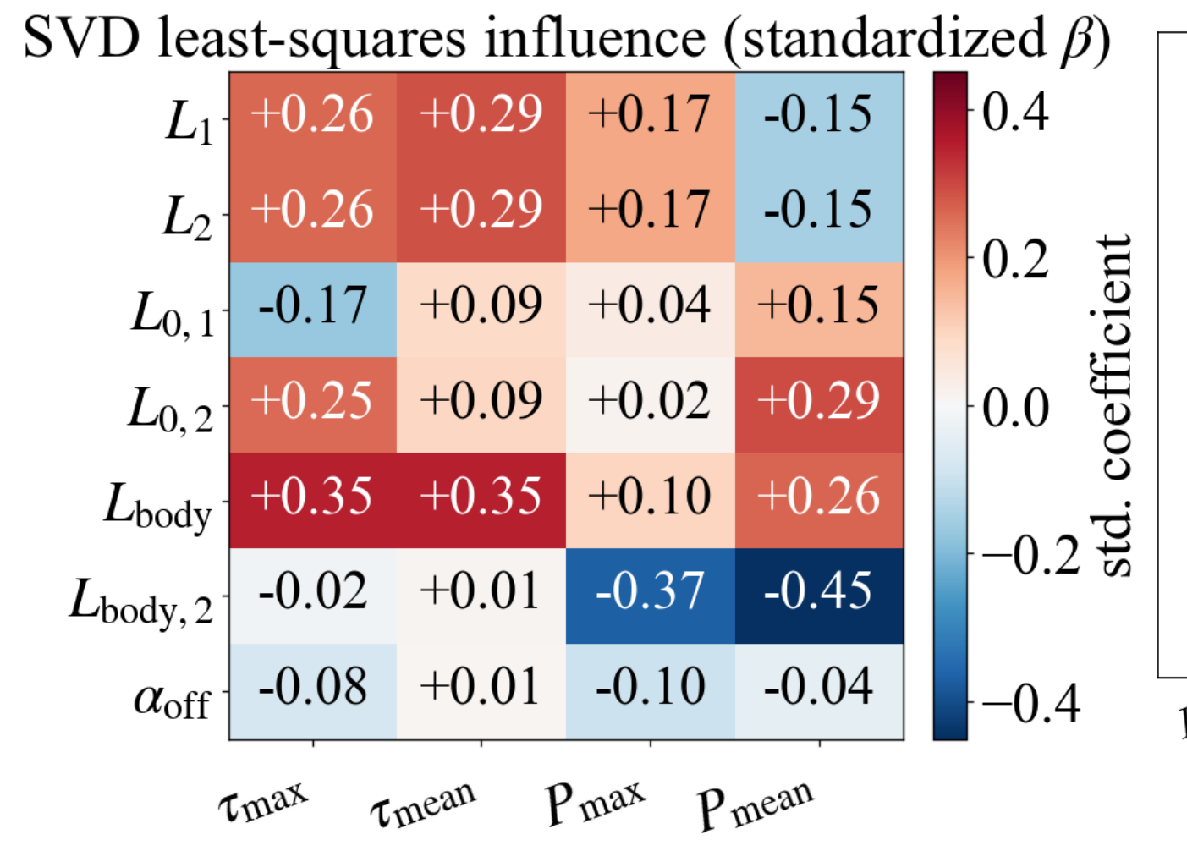
SVD least-squares influence (standardized β)

	τ_max	τ_mean	P_max	P_mean
L_1	+0.47	+0.39	+0.19	+0.11
L_2	+0.47	+0.39	+0.19	+0.11
$L_{0,1}$	+0.09	+0.39	+0.36	+0.69
$L_{0,2}$	+0.09	-0.12	-0.16	-0.28
L_body	+0.04	+0.06	+0.04	+0.02
$L_{\mathrm{body},2}$	-0.16	+0.15	-0.24	+0.01
α_off	+0.01	-0.01	+0.03	+0.09

straight-line climbing



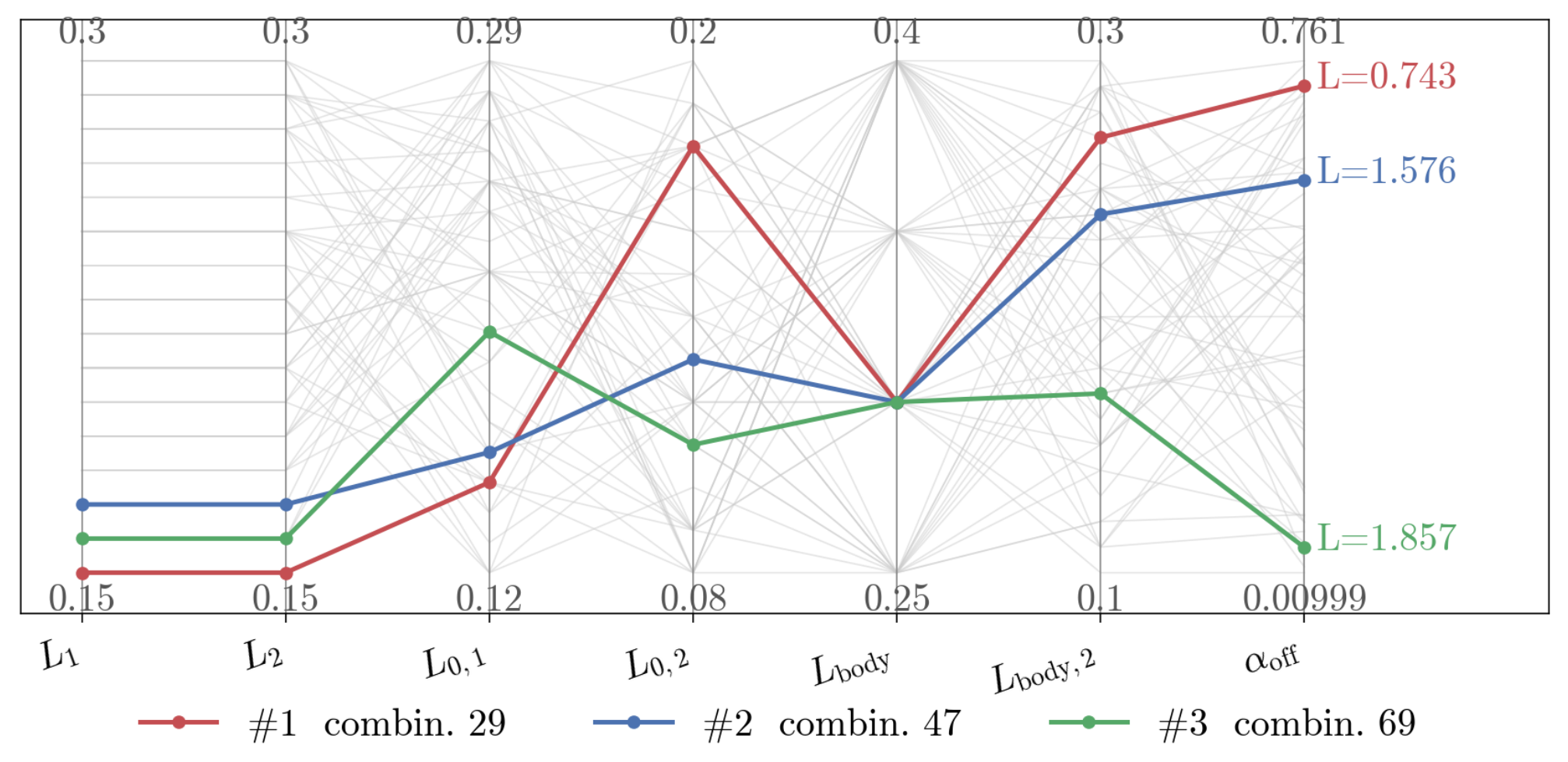
switching motion



SVD least-squares influence (standardized β)

	τ_max	τ_mean	P_max	P_mean
L_1	+0.26	+0.29	+0.17	-0.15
L_2	+0.26	+0.29	+0.17	-0.15
$L_{0,1}$	-0.17	+0.09	+0.04	+0.15
$L_{0,2}$	+0.25	+0.09	+0.02	+0.29
L_body	+0.35	+0.35	+0.10	+0.26
$L_{\mathrm{body},2}$	-0.02	+0.01	-0.37	-0.45
α_off	-0.08	+0.01	-0.10	-0.04

parameter ranking



7. Results

- Results clarify numerically the trade-off between for shorter limbs between reduced torque demands and reachability
- Axial offset $L_{0,1}$ at shoulder affects peak power
- In the studied parameter range, torso dimensions are not critical
- Motion-dependent parameter influence on torques (see $L_{\mathrm{body},2}$)
- Best combination: peak torque of 9.7 Nm
- The design question therefore resolves to the shortest limbs that still satisfy the reach requirement, with the shoulder offset traded against peak power

8. Open Questions

- How many limbs and grippers should a climbing robot have?
- How does such a system behave dynamically?
- Can closed kinematic chains reduce peak torque demands by distributing the load?
- Does this offset the added load?
- Improve understanding of dual (multi)-arm systems in climbing contexts.

→ Paper coming soon

LUT University

Limitations

Rigid bodies and ideal grippers; grasp forces are assumed sufficient and left to the gripper design. Trajectories are prescribed rather than optimised. No payload or tool mass, and no variation in tube diameter or connector geometry of the kind a real scaffold presents.

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