A Step Towards Generating Human-Like Walking Gait via Trajectory Optimization through Contact for a Bipedal Robot with One-Sided Springs on Toes

Kenneth Chao and Pilwon Hur

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TEXAS A&M UNIVERSITY

Outline

- Motivation and background
- Trajectory optimization through contact
- Modified framework
  - Hermite-Simpson method
  - Cost function for virtual flexible components
  - Complementary constraints for one-sided springs
- Result, conclusion and future work

Motivation and background

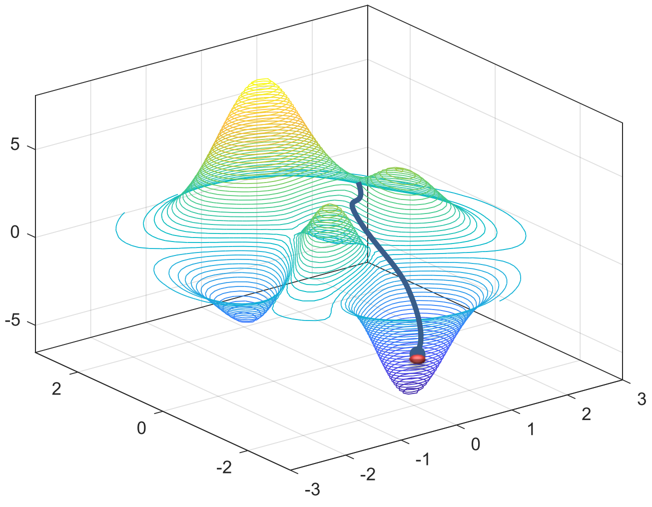
Generating an efficient, robust walking gait with multiple contact domains is challenging

- The floating-based system is complex
  - High dimensions and nonlinearity
  - Non-convex constraints in kinematics and dynamics
- Existence of contact impact
- Combination of different contact domains
  - Different contact conditions (constraints) result in different dynamics
  - Mixture of full, over, or under actuation

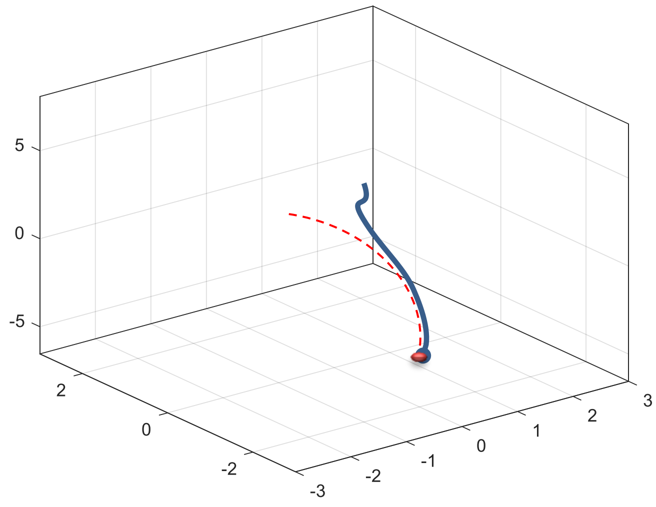
Motivation and background

- Optimal control and trajectory optimization

closed-loop solution u = u(x)



open-loop solution u = u(t)



global optimal solution
hard to compute
lower dimensional problems

local method, suboptimal solution
easier to compute
higher dimensional problems

Motivation and background

- Trajectory optimization is the collection of methods used to find the best choice of trajectory: x(t) and u(t)
  - Single shooting
  - Multiple shooting
  - Direct collocation

More accurate, harder to pose and solve

Less accurate, easier to pose and solve

Continuous functions of time → Discrete set of real numbers

$$
\begin{aligned}
t &\rightarrow [t_0, t_1, \ldots, t_N] \\
x(t) &\rightarrow [x_0, x_1, \ldots, x_N] \\
u(t) &\rightarrow [u_0, u_1, \ldots, u_N]
\end{aligned}
\qquad
\begin{aligned}
t &= \text{grid point number} \\
x_k &= x(t_k) \\
u_k &= u(t_k)
\end{aligned}
$$

State of the arts: Trajectory optimization for walking motion generation with multiple contact domains

- Hybrid Zero Dynamics (HZD)-based trajectory optimization with direct collocation (Ames et al. 2015-16)

- Trajectory optimization through contact
  (Posa et al. 2012)

State of the arts: Trajectory optimization for walking motion generation

	HZD-based	Optimization through contact
Trajectory optimization approach	Direct collocation method	
Optimization objective	Minimizing cost of transport (CoT) $$CoT(\mathbf{x}) = \frac{\text{Energy}}{\text{Weight} * \text{Distance}} = \frac{1}{mgd} \sum_{k=1}^{N} \sum_{i} \lvert u_{k,i} \dot{q}_{k,i} \rvert$$	

State of the arts: Trajectory optimization for walking motion generation

	HZD-based	**Optimization through contact**
Impact handling	Hybrid-invariant constraints for phase-switchings	Time-stepping method
Predefined contact sequence	Required	Not required
Result sensitivity to initial guess	Relatively low	Relatively high
Transcription method for collocation	Hermite-Simpson method (cubic splines)	Trapezoid method (linear functions)

Trajectory optimization through contact

$$\underset{x=\{h, x_0, \dots, x_N, u_1, \dots, u_N, \lambda_1, \dots, \lambda_N\}}{\text{minimize}} \quad CoT(x)$$

time step

$$G(x) \geq 0$$
$$H(x) \geq 0$$
$$G(x)^T H(x) = 0$$

Complementary constraints for contact, e.g.

$$toe_{height}(x) \geq 0$$
$$F_{toe} \geq 0$$
$$toe_{height}(x) F_{toe} = 0$$

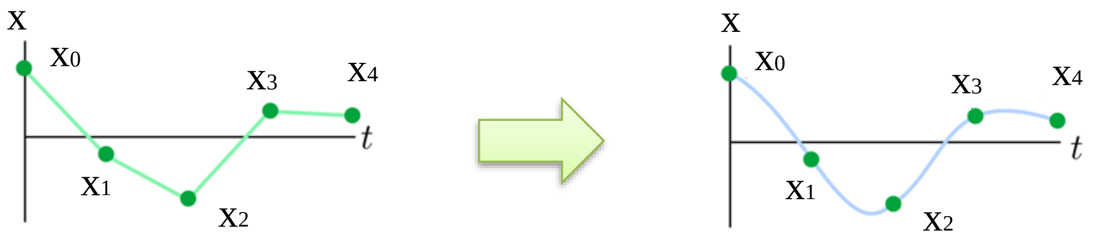
Kinematic, dynamic constraints, and periodic constraints

Modified framework

- Hermite-Simpson method
- Cost function with virtual flexible components
- Complementary constraints for one-sided springs

Modified framework (1/2)

- Hermite-Simpson method



- Cost function with virtual flexible components

$$cost(\mathbf{x}) = \underbrace{\frac{1}{mgd} \sum_{k=1}^{N} \sum_{i} |u_{k,i} \dot{q}_{k,i}|}_{CoT(x)} + \omega \sum_{k=1}^{N} u_k^T u_k$$

$$\omega \sum_{k=1}^{N} (u_k - kB_k q_k)^T (u_k - kB_k q_k)$$

Modified framework (2/2)

- Complementary constraints for one-sided springs

$$G(x) \geq 0$$
$$H(x) \geq 0$$
$$G(x)^T H(x) = 0$$

$$k_{toe}\theta_{toe} = (T_1 + T_2) - T^-$$
$$(T_1 + T_2)T^- = 0$$
$$T_1 T_2 = 0$$
$$\phi_{z,toe} T_1 = 0$$
$$\phi_{z,toe}, T_1, T2, T^- \geq 0$$

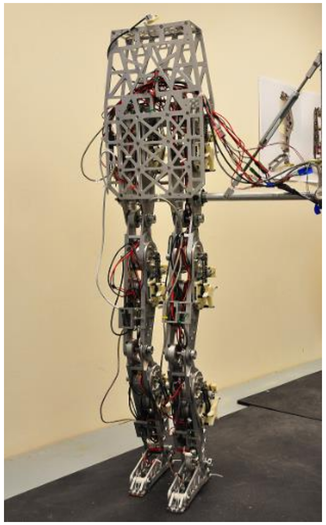
$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = Bu + J^T\lambda - J^T_{\theta,toe} T_1$$

Software and Hardware

Hardware (robot model)

Planer bipedal robot Amber 3

- Height: 1.45 m
- Weight: 33.4 Kg
- 7-link, 6 DOFs



Software

- MATLAB and mathematica
- Opt Solver
  - IPopt
  - fmincon in MATLAB

Optimization overview

Opt. Problem Summary

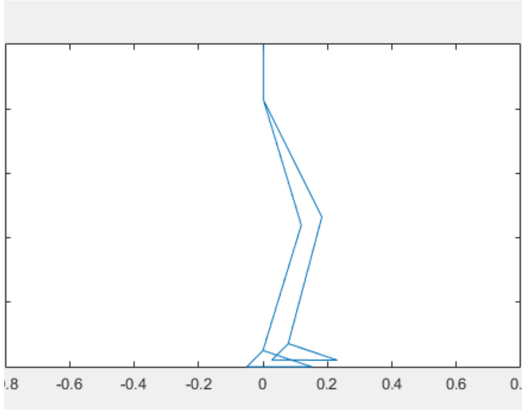
- Time duration: a half gait cycle
- 31 (discretized) collocation points
- 1334 free variables, 1709 constraints
- Can be solved in 1-6 minutes*

Initial guess: ZMP-based flat-feet walking gait

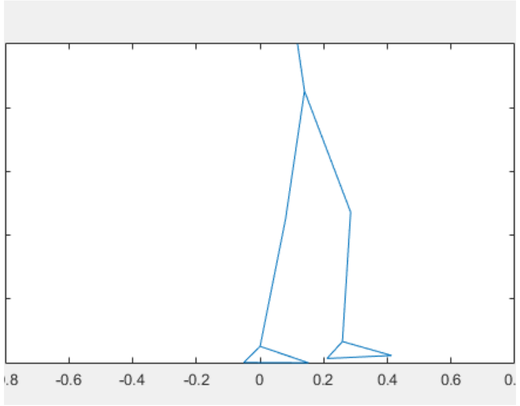
Testing different set of contact constraints

- Sliding allowed contact constraints (SACC)
- Non-sliding contact constraints (NSCC)
- NSCC with one-sided springs (OSS)

Simulation Result (1/2)



Initial guess

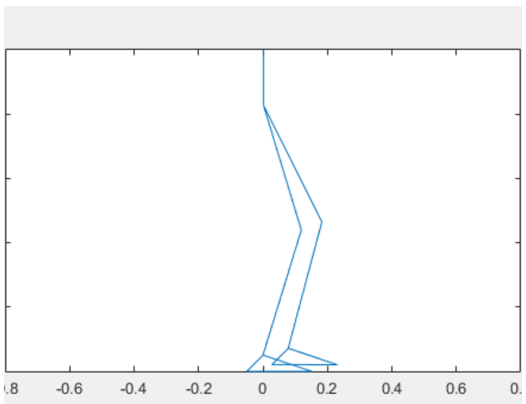


SACC

	Initial guess	**SACC**	**NSCC**	**OSS**
Cost	0.577	0.048	0.049	2.644
Step length (m)	0.2	1.10	1.0	1.0

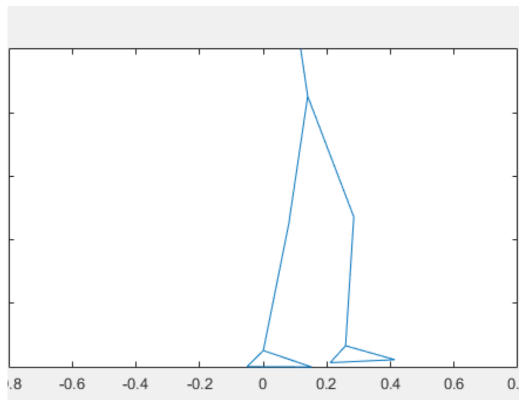
Simulation Result (2/2)

$$
\begin{aligned}
\min_{X} \quad & \sum (q_k - q_{k_ref})^T (q_k - q_{k_ref}) \\
\text{s.t.} \quad & toe_{height} \geq f(toe_{horizontal}) \\
& heel_{height} \geq f(heel_{horizontal}) \\
& \text{Hermite-Simpson constraints}
\end{aligned}
$$



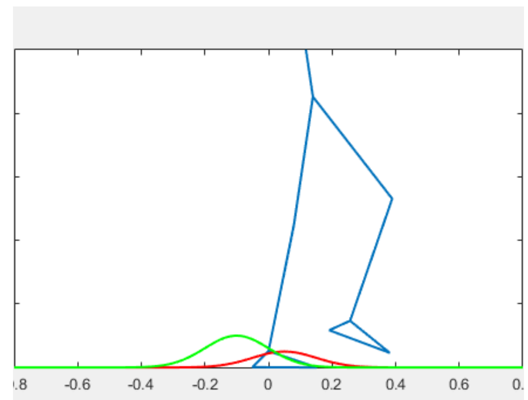
Initial guess

$Cost \approx 0.5$



Optimization through contact with SACC

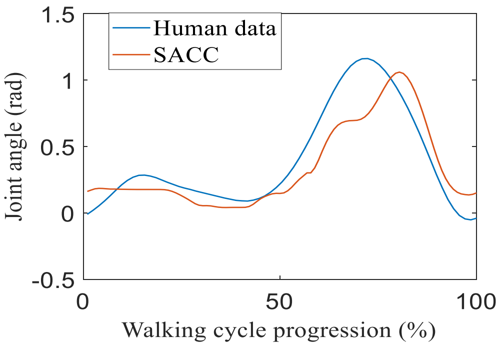
$Cost \approx 0.047$



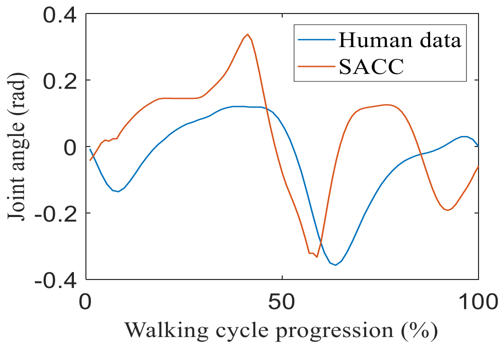
Modified result from a kinematics-based optimization

Joint trajectories comparison to human data

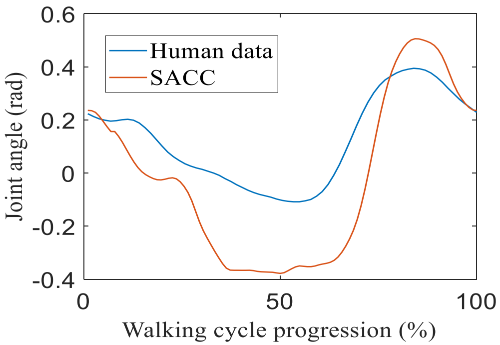
- Result from Opt. with SACC and post-processing Opt.



Knee joint

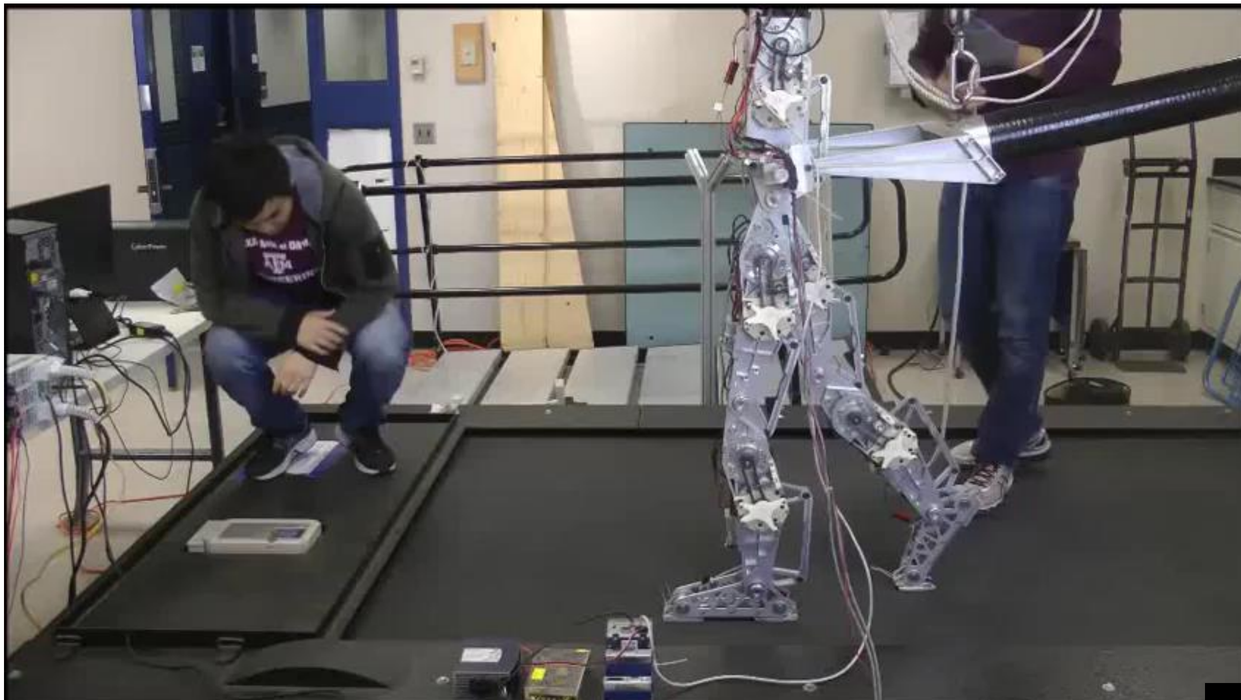


Ankle joint



Hip joint

Current Experiment Result
(Not completely successful)



Conclusion and Future works

- The modified framework increases the accuracy of kinematic and dynamic approximation, and several schemes are provided and tested altering the walking behavior
- Further modifications of model and constraints (e.g. for increasing foot clearance) are required for more natural generated walking gait
- A better opt solver for handling optimization with complementary constraints and its relaxations is required
- Implementations on bipedal robot and lower limb prosthesis as validation

Thank you for your attention!

- Q&A