Bipedal Locomotion Optimization by Exploitation of the Full Dynamics in DCM Trajectory Planning

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Problem Statement

Trajectory planning approaches:

- Full dynamic model
- Simplifed dynamic model
    - LIPM and DCM concepts

In DCM trajectory planning, several parameters need to be set.

Simulation-based trajectory optimization considerations:

- Full dynamic model
- Foot-Ground contact model

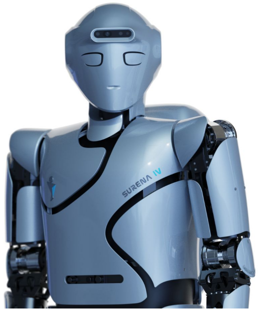

Figure 1: Surena IV humanoid robot

LIP Model and DCM Concept

LIPM Assumptions:

- Constant Height
- Concentrated Mass
- Zero Momentum about the Center of Mass

$$\ddot{x} = \omega^2 (x - r_{ZMP}) \tag{1}$$

Considering ξ as a state variable:

$$\begin{cases} \dot{\xi} = \omega(x - r_{ZMP}) \\ \dot{x} = -\omega(x - \xi) \end{cases} \tag{2}$$

The first equation of (2) is unstable and that is why ξ is called Divergent Component of Motion (DCM).

Trajectory Generation

DCM time domain equation:

$$\xi(t) = r_{ZMP} + e^{\sqrt{\frac{g}{z_0}}t}(\xi_{init} - r_{ZMP}) \tag{3}$$

Initial DCM positions are calculated recursively:

$$\xi^i_{init} = \xi^{i-1}_{end} = r^i_{ZMP} + e^{-\sqrt{\frac{g}{z_0}}t_{step}}(\xi^i_{end} - r^i_{ZMP}) \tag{4}$$

for double support phase, we used a 3rd degree polynomial:

$$\begin{cases} \xi^i_{init,DS} = r^{i-1}_{ZMP} + e^{-\sqrt{\frac{g}{z_0}}t_{(\Delta t_{init,DS})}}(\xi^i_{init} - r^{i-1}_{ZMP}) \\ \xi^i_{end,DS} = r^i_{ZMP} + e^{-\sqrt{\frac{g}{z_0}}t_{(\Delta t_{end,DS})}}(\xi^i_{init} - r^i_{ZMP}) \end{cases} \tag{5}$$

$$\Delta t_{init,DS} = \alpha t_{DS}, \Delta t_{end,DS} = (1 - \alpha) t_{DS}$$

Trajectory Generation

CoM trajectory could be find by integrating the second equation of (2):

$$x(t) = e^{-\sqrt{\frac{g}{z_0}}t}\left(x(0) + \sqrt{\frac{g}{z_0}} \int e^{\sqrt{\frac{g}{z_0}}t} \xi(t) dt\right) \tag{6}$$

Also for ankle trajectories, we utilized a 5th degree polynomial.

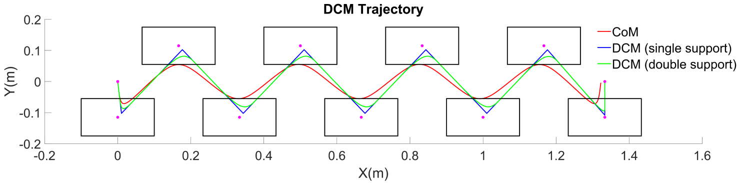

Figure 2: Schematic of planned trajectories

Optimization Problem

Optimization Parameters:

Table 1: Optimization Parameters and their search region

	α	r_{DS}	$t_{step}(s)$	$z_0(m)$	$h_{ankle}(m)$
min	0.2	0.1	0.5	0.65	0.025
max	0.7	0.5	1.3	0.7	0.075

Constraints:

- Robot’s joints workspaces
- Maximum output torque of actuators
- Robot’s center of mass height
- Constant walking speed

Optimization Problem

Objective Functions:

$$J_E = -\sum_{i=1}^{12} E_i,\ J_{torque} = -\sum_{i=1}^{12} T_i,\ J_{vel} = -\sum_{i=1}^{12} \dot{q}_i \tag{7}$$

$$\begin{cases} J_{ZMP} = -r(p_{ZMP}, V) \ \ if\ ZMP\, is\ inside \\ J_{ZMP} = r(p_{ZMP}, V) \ \ if\ ZMP\, is\ not\ inside \end{cases} \tag{8}$$

These objective functions will be calculated during a limited time (5s) of continuous walking on a straight line by considering the full dynamics and foot-ground contact models in PyBullet Simulation.

Single and Multi-Objective Optimization

- First, each objective function optimized with the single objective GA
- With the help of multi-objective optimization, we can optimize J_E and J_{ZMP} simultaneously

Table 2: Optimization algorithms parameters

Algorithm	Population size	Crossover Type	Mutation Type	Elitisms
GA	100	Uniform (0.8)	Rand (0.08)	0.03
NSGA-II	150	Simulated Binary (0.9)	polynomial	0.0

ROS Based Framework

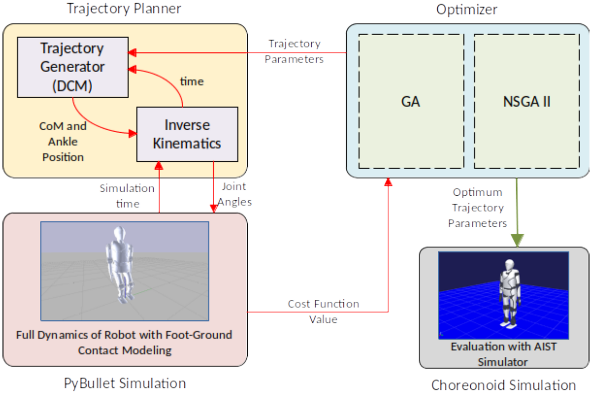

Figure 3: Schematic of the developed framework

Single Objective Results

Table 3: Single objective optimization results

α	r_{DS}	t_{step}	z_0	h_{ankle}	Objective Value
0.42	0.3	1.09	0.696	0.026	$J_E = 30.714KJ$
0.26	0.1	1.25	0.696	0.025	$J_{torque} = 3348N.m$
0.48	0.33	1.19	0.699	0.036	$J_{vel} = 155228\frac{rad}{s}$
0.38	0.1	0.6	0.658	0.036	$J_{ZMP} = -132.54m$

- h_{ankle} and z_0 are almost equal to the minimum and maximum values allowed for these parameters.
- J_E aligns with J_{torque} and J_{vel}

Multi-Objective Results

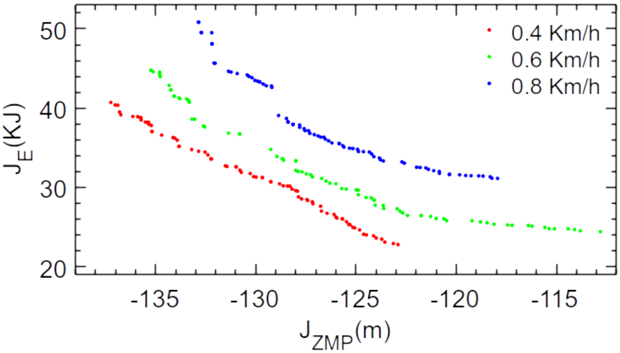

Figure 4: Pareto set of the multi-objective optimization

Multi-Objective Results

The optimal parameters for some of the points which have good results both in terms of energy and stability:

Table 4: Multi-objective optimization results

speed $(\frac{Km}{h})$	α	r_{DS}	t_{step}	z_0	h_{ankle}	Objective Values
0.4	0.44	0.1	0.74	0.699	0.033	$J_E = 31.175KJ, J_{ZMP} = -129.7m$
0.6	0.69	0.1	1.05	0.677	0.025	$J_E = 32.079KJ, J_{ZMP} = -127.9m$
0.8	0.69	0.1	1.04	0.683	0.025	$J_E = 36.278KJ, J_{ZMP} = -126.7m$

Choreonoid Simulation Results

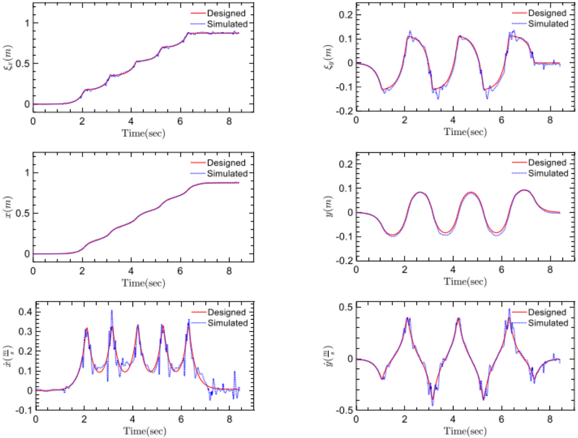

Figure 5: Designed and simulated trajectories

Conclusion and Future Works

In this paperwe developed a framework to obtain optimal parameters for trajectory planning based on DCM.

- We Considered full dynamic and foot-ground contact model in the simulation.
- With the help of the obtained results, we can design the robot trajectory to move online with the most stability or the lowest energy consumption.
- With the help of multi-objective optimization embedded in the framework, we obtained trajectory parameters that compromise these two objectives at three different speeds.
- We plan to design the optimal trajectory under different conditions, such as moving on uneven and slippery surfaces or soft surfaces for future works. And controlling robot's motion while rejecting output disturbances is another goal of the team for the future

Thanks

Doubts and Suggestions

https://github.com/CAST-Robotics/Trajectory-Optimization

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