

State Feedback Controllers

Overview

This project implements a **humanoid walking controller** based on a controller proposed in a research paper, modeled and validated using **MATLAB/Simulink**. The model is designed as an **educational and reproducible reference**.

Motivation & Objectives

Humanoid walking is a challenging control problem due to:

- Nonlinear dynamics
- Underactuated systems
- Stability requirements (balance and ZMP/CoP constraints)

Objectives of this project:

- Implement the walking controller described in the reference paper
- Validate the controller in MATLAB/Simulink
- Visualize walking performance using key metrics such as CoM, CoP, and ZMP

Reference Papers

The controllers implemented in this project are based on the following key research works:

1. **Q.-C. Zhong and D. Rees**, *Control of Uncertain LTI Systems Based on an Uncertainty and Disturbance Estimator*, ASME Journal of Dynamic Systems, Measurement, and Control, 2004.
2. **J. P. Kolhe et al.**, *Disturbance Estimation Based Robust Center of Mass Tracking Control of Humanoid Robot*, IFAC PapersOnLine, 2024.

Controllers Implemented

This project implements and compares **two walking controllers** for humanoid CoM trajectory tracking:

1. **State Feedback Controller (SFC)** – baseline controller
2. **State Feedback Controller with Uncertainty and Disturbance Estimator (SFC + UDE)** – robust controller

Both controllers are implemented as **separate Simulink models** and evaluated under identical conditions to highlight performance differences.

Theory Background

1. State Feedback Controller (SFC)

Overview

The **State Feedback Controller (SFC)** is a classical control approach used as a baseline for humanoid Center of Mass (CoM) trajectory tracking. It assumes that the system dynamics are well known and that all required state variables are available for feedback.

Key Assumptions

- The humanoid robot is modeled using a simplified **Linear Inverted Pendulum Model (LIPM)**.
 - The Center of Mass (CoM) height remains constant during walking.
 - All system states (CoM position and velocity) are measurable.
 - External disturbances and model uncertainties are negligible.
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Control Principle

- The controller uses **state feedback** to regulate the CoM motion.
 - A desired CoM trajectory is provided by a reference generator.
 - The controller computes the control input such that the tracking error follows a stable second-order dynamic behavior.
 - Controller gains are selected to achieve desired transient performance such as settling time and damping.
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Characteristics of SFC

- Simple and easy to implement.
 - Computationally efficient.
 - Effective when the model accurately represents the system.
 - Commonly used as a **baseline controller** for comparison.
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Limitations of SFC

- Sensitive to external disturbances such as pushes or ground reaction forces.
 - Performance degrades in the presence of modeling errors.
 - Limited robustness for real-world humanoid walking scenarios.
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2. State Feedback Controller with Uncertainty and Disturbance Estimator (SFC + UDE)

Overview

The **State Feedback Controller with UDE (SFC + UDE)** is an enhanced version of the SFC designed to improve robustness. It explicitly estimates and compensates for unknown disturbances and model uncertainties affecting the humanoid robot during walking.

Motivation for UDE Augmentation

- Humanoid robots operate in uncertain environments.
 - External disturbances such as pushes, uneven terrain, and interaction forces cannot be avoided.
 - A purely model-based controller like SFC cannot handle these uncertainties effectively.
 - UDE provides a systematic way to estimate and cancel these effects in real time.
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Control Principle

- The nominal SFC structure is retained.

- An **Uncertainty and Disturbance Estimator (UDE)** is added to the control loop.
 - The UDE observes the combined effect of disturbances and uncertainties using system states and control inputs.
 - A low-pass filtering mechanism is used to estimate disturbances without amplifying noise.
 - The estimated disturbance is fed back into the control input to cancel its effect.
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Characteristics of SFC + UDE

- Explicit estimation and compensation of disturbances.
 - Improved robustness against external forces and modeling errors.
 - No direct measurement of disturbances is required.
 - Maintains the same desired tracking behavior as the nominal SFC.
 - Produces smoother control actions compared to delay-based disturbance estimation methods.
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Advantages over SFC

- Significantly reduced CoM tracking error under disturbances.
- Enhanced walking stability.
- Better performance during push-recovery scenarios.
- More suitable for practical humanoid walking applications.

Both controllers are implemented as separate Simulink models and evaluated under identical conditions to highlight performance differences.

How to Run the Simulation

Step 1: Open MATLAB

Set the project root directory as the MATLAB working directory.

```
\State Feedback Controllers\SFC  
OR  
\State Feedback Controllers\UDE_SFC
```

Step 2: Initialize Parameters

Run the initialization script:

```
ref_data_zir.m ---file
```

Step 3: Open Simulink Model

Open the Simulink file:

```
slipm3D_zir.slx
```

Step 4: Run Simulation

Click **Run** in Simulink

Outputs & Results

To visualize and analyze the simulation results click on the **Simulink scopes in model**.

Or open

```
State Feedback Controllers\Snapshots_SFC&SFC_UDE --Folder
```

Comparison between Two Controllers

Open

```
State Feedback Controllers\comp_ude_SFC -- Folder
```

Run

```
Compare_SFC_SFCude.m -- File
```

