Comparative Analysis of Full-body Legged Stability Using Balanced and Steppable Regions

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PROBLEM STATEMENT

- Given: SYSTEM, DESIRED CONTACTS, SYSTEM STATE (position & velocity)
- Questions: BALANCED or UNBALANCED?
  And if the current contact configuration must be broken: Can a step be taken? STEPPABLE or FALLING?
- Solution: CONTACT-DEPENDENT STATE SPACE PARTITION

STATES OF BALANCE – DEFINITIONS

- BALANCED vs. UNBALANCED states are defined relative to a specified contact configuration [1]:
  BALANCED state: There exists a (controlled) trajectory starting from a given legged system’s state such that the system does not ever alter its contacts
  UNBALANCED state: All (controlled) trajectories starting from a given legged system’s state will lead to an inevitable change in the system’s contacts [2]
  - STEPPABLE state: There exists a (controlled) trajectory starting from a given legged system’s state such that the swing foot can reach the desired step length before other contacts are made
  - FALLING state: All (controlled) trajectories starting from a given legged system’s state do not allow the swing foot to reach the desired step length before other contacts are made

STEPPABILITY vs. CAPTURABILITY: ability to step vs. come to a stop [3] [4]
- Steppability complements capturability
- Inverse problem: final stepped state → initial COM states and vice versa
- Incorporation of full-body, system-specific, nonlinear characteristics and capabilities (e.g., joint and actuation limits and angular momentum)
- Iterative application for step-by-step analysis of a sequence of N steps

STABILITY REGIONS – MODELS AND CONSTRUCTION ALGORITHMS

- Balanced or steppable stability region: state space partition between balanced and unbalanced states or steppable and falling states relative to a specified contact configuration
- Stability boundary: set of maximum allowable center of mass (COM) velocity perturbations to maintain balance without undesired changes in contacts

RESULTS AND DISCUSSION

- Comparative analysis of biped robot vs. human stability regions

COM Trajectory

- SS Balanced
- SS Phase
- DS Balanced
- DS Phase

Normalized COM X-position (by average COM Y-height)

Figure 3: Normalized steppable, SS balanced, DS balanced, and 1-step capture regions for the DARwIn-OP humanoid robot vs. human subject with respect to walking COM trajectories at desired step lengths of 0.057 m and 0.74 m, respectively. Balanced region (blue points) and rolling COM trajectory of a rimless wheel are shown for comparison (bottom right).

- Comparative analysis of steppability vs. capturability

Figure 4: Steppable and 1-step viable capture basins for reduced-order models (center inset) of robot vs. human at varying COM X-positions (left) and initial poses (center). Two hypothetical trajectories are shown where the system is captured after two steps and N steps (right).

CONCLUSIONS

- Balanced and steppable stability region analysis accounts for:
  - System-specific capabilities, limitations, and nonlinearity
  - Full-body system dynamics
  - Characteristic COM regulation and angular momentum effects

REFERENCES


ACKNOWLEDGEMENTS

Figure 2: Stability region (blue) in the 6-dimensional COM state space

Figure 3: Stability region (blue) in the 6-dimensional COM state space

Figure 4: Stability region (blue) in the 6-dimensional COM state space