Robust Execution of Temporally Flexible Plans for Bipedal Walking Devices

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Problem Statement and Background

Problem Statement

-Execute bipedal walking plans that specify
  - -State-space constraints
  - -Temporal constraints
-Exploit plan flexibility to compensate for disturbances
-Detect conditions that lead to plan failure

Walking task execution is different from simple periodic walking

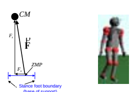
Challenges

-Highly nonlinear mechanism

$$\mathbf{H}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) = \boldsymbol{\tau}$$

-High dimensional
  - -18 D.O.F., 36 state variables

-Limited balance capability due to
  - -High center of mass
  - -Limited support base



The limited support base imposes an actuation constraint on the horizontal balancing force that can be exerted on the center of mass.

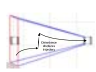
Background

Robot motion control systems [1]

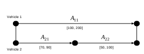
-Joint reference trajectories computed off-line
-Tracked closely by high-impedance controllers
-Advantages: take dynamics into account
-Disadvantages: too rigid, not flexible to disturbances

Flow tube systems [2]

-Extend reference trajectory to set of trajectories
-Advantages: flexible, robust to disturbances
-Disadvantages: no time flexibility, limited to small problems



Temporally flexible plan execution systems [3]

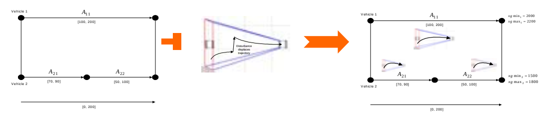


-Combined off-line/on-line methodology
-Compilation makes explicit the family of schedules that satisfy the plan
-Dispatcher dynamically updates this family of schedules in response to disturbances that occur during execution
-Advantages: time flexibility, capable of solving large problems
-Disadvantages: ignores continuous dynamics, actuation limits

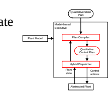
Approach and Methods

Approach

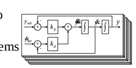
-Combine the capabilities of temporally flexible plan execution systems, with those of flow tube systems



-Use a model-based executive [4]
  - -Inputs: *Qualitative state plan* (QSP), plant model, and current plant state
  - -Outputs: control actions for the *abstracted plant*
  - -Compiler generates *qualitative control plan* (QCP) based on QSP and plant model

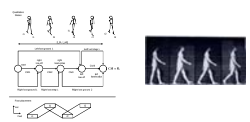


-Use an enhanced feedback linearizing controller [5] to
  - -Linearize and decouple the actual plant
  - -Abstracted plant: set of loosely coupled SISO systems
  - -Constraints depend on discrete mode of plant
  - -Discrete mode defined by base of support
    - -Changes discontinuously with each step

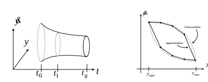


$$y_{set\_\min} \le y_{set} \le y_{set\_\max}$$
$$\dot{y}_{set\_\min} \le \dot{y}_{set} \le \dot{y}_{set\_\max}$$
$$k_{p\_\min} \le k_p \le k_{p\_\max}$$
$$k_{d\_\min} \le k_d \le k_{d\_\max}$$
$$\ddot{y} = k_p(y_{set} - y) + k_d(\dot{y}_{set} - \dot{y})$$

-Qualitative State Plan
  - -Set of activities that connect events
  - -Temporal constraints on events
  - -State-space constraints associated with activities
    - -Define legal foot placements



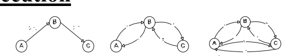
-Qualitative Control Plan
  - -Dispatchable graph [3]
  - -Concurrent timed flow tubes for activities
  - -Flow tube represented by set of cross sections in SISO system position-velocity phase space
  - -Cross section approximated by polyhedron



Compilation and Execution

Compilation

-Compute dispatchable graph [3]



-Compute flow tubes for each activity
  - -Compute cross section for each time increment in [l,u] in graph
  - -Use LP formulation

SISO dynamics

$$y = e^{\alpha t}\left(K_1 \cos\beta t + iK_2 \sin\beta t\right) + u/c$$
$$\dot{y} = e^{\alpha t}\left(\beta\left(-K_1 \sin\beta t + iK_2 \cos\beta t\right) + \alpha\left(K_1 \cos\beta t + iK_2 \sin\beta t\right)\right)$$
$$K_1 = y(0) - u/c,\ K_2 = (i/\beta)\left(\alpha K_1 - \dot{y}(0)\right)$$
$$\alpha = -k_d/2,\ \beta = \left(-i\sqrt{k_d^2 - 4k_p}\right)/2,\ u = k_p y_{set} + k_d \dot{y}_{set}$$

Actuation constraints

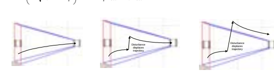
$$y_{set\_\min} \le y_{set} \le y_{set\_\max}$$
$$\dot{y}_{set\_\min} \le \dot{y}_{set} \le \dot{y}_{set\_\max}$$

Goal region constraints

$$\langle y, \dot{y} \rangle \in R_{goal}$$

Execution

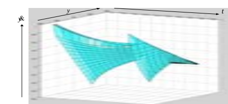
-Dispatcher tries to keep trajectory in flow tube
-Adjusts control parameters to do this
-If disturbance pushes trajectory out of tube, then adjustment is not possible – plan execution fails



Results and Discussion

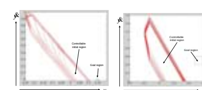
Results

Flow tubes represent feasible trajectory set

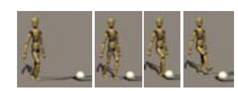


Dispatcher selects from this set to compensate for disturbances

If state lies within initial region of multiple flow tubes, dispatcher may select any. By selecting appropriate flow tube, the dispatcher is able to adjust the time of goal region arrival. This is useful for synchronizing task execution.



Initial cross sections for activity for taking a step (lateral movement left, forward movement right)



By selecting the appropriate tube, the dispatcher Moves the biped so that it is in the right place at the Right time to kick the moving soccer ball.

Discussion

Approach is suitable for general class of problems

-Plan with flexible state-space and temporal constraints
-Hybrid plant (discrete and continuous state variables, dynamic)
-Plant transformable into loosely coupled SISO set
-Actuation limits result in temporal constraints due to plant dynamics, which interact with temporal constraints imposed by plan

Bipedal walking plan execution is an example of this class of problem

References

[1] J. Yamaguchi, N. Kinoshita, A. Takanishi, and I. Kato. "Development of a dynamic biped walking system for humanoid – development of a biped walking robot adapting to the human's living floor". *IEEE International Conference on Robotics and Automation* (ICRA)

[2] E. Bradley and F. Zhao. Phase-space control system design. *Control Systems*, 13(2),39-46 April, 1993

[3] N. Muscettola, P. Morris, and I. Tsamardinos. Reformulating temporal plans for efficient execution. *Proc. Of Sixth Int. Conf. On Principles of Knowledge Representation and Reasoning*, 1998

[4] T. Leaute, B. Williams. Coordinating Agile Systems Through the Model-based Execution of Temporal Plans. ICAPS, 2005

[5] A. Hofmann, S. Massaquoi, M. Popovic, and H. Herr. A sliding controller for bipedal balancing using integrated movement of contact and non-contact limbs. *Proc. International Conference on Intelligent Robots and Systems* (IROS). Sendai, Japan