Dynamic Maneuvers in a 3D Galloping Quadruped Robot

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Dynamic Maneuvers

- Sudden changes in trajectory or speed
- Turning, sudden starts/stops, running jumps
- Initiating, terminating, or interrupting high-speed dynamic locomotion
- Difficulty: Dynamic stability, hybrid control dynamics, hard to observe in nature
Objectives

- Find solutions to dynamic maneuvers
  - High-Speed Turn
  - Running Jump
  - High-speed running gait (Gallop)
- Develop flexible control architecture
- Use multiobjective genetic algorithm (MOGA)

Dynamic Model

- Articulated legs with 3 DOF, nonzero mass
- Asymmetric body mass
- Passive knee compliance
- Compliant contact model
- Static, kinetic friction
Dynamic Simulation

- Dynamic simulation used to compute quadruped robot dynamics
- *DynaMechs* package developed by Scott McMillan – used for recursive dynamics computation

Controller Architecture

- Modular, hierarchical structure
- Flexible: Define cyclic or one-shot behaviors
- Low-level motor primitives defined for each leg
  - Basic movements for running or maneuvering
  - Minimal parameters vs. maximum functionality
Leg Primitive Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
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<tbody>
<tr>
<td>FREE</td>
<td>Allow all joints to move freely.</td>
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<tr>
<td>TRANSFER</td>
<td>Transfer all joints from initial to desired ending positions over period $T$ using a cubic spline.</td>
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<tr>
<td>EARLY-RETRACTION</td>
<td>Rotate hip rearwards at desired tangential velocity.</td>
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<tr>
<td>STANCE-CONTROL</td>
<td>Maintain desired tangential velocity of foot; maintain touchdown ab/ad angle; achieve desired knee energy at max compression.</td>
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The Genetic Algorithm

- Genetic algorithm (GA) overview
  - Direct random search of unknown parameter space
  - Parameters encoded in a chromosome
  - Chromosome is altered via genetic operators
  - Algorithm similar to Darwinian evolution
    - Each chromosome considered an individual
    - Group of all individuals considered a population
    - Population changes over several generations via genetic operators
    - Individuals ranked according to their fitness with the best performers able to reproduce
Genetic Operators

• **Selection**: Fittest individuals get to reproduce
  – Elitism used to preserve the best individual(s)
  – Fitness-proportionate (Roulette-wheel) selection
    • Higher fitness $\rightarrow$ better selection probability
  – Multiple copies of fittest individuals in mating pool

Genetic Operators (cont’d)

• **Crossover**: Individual *genes* are swapped between two parents to form two new children

• **Mutation**: Genes of each individual are randomly changed with a probability $p_m$
GA Summary

For Generation = 1 to N \( N = 250 \) max

1. Evaluate fitness of all \( S \) individuals in the population \( S = 32 \)
2. Select fittest individuals for mating pool
3. Crossover individuals in mating pool with probability \( p_c \) (60%)
4. Mutate each individual’s genes with probability \( p_m \) (5%)

Multiobjective Genetic Algorithm

- Trade-offs among multiple criteria
- Vector-valued fitness
  \( f = [f_1, f_2, \ldots, f_n]^T \)
- Pareto front: set of non-dominated solutions
  - Domination: One solution \( \geq \) the other in each position, \( > \) in at least one position

Example of a Pareto Front.
The Gallop

- Preferred gait for high-speed quadrupedal locomotion
- Asymmetric footfalls (e.g., LR-RR-LF-RF)
- At least one flight phase (gathered)
- Early retraction of limbs
- Smoother than trot, bound

The Turn

- State machine approach
- Control parameters (12)
  - Four touchdown ab/ad angles
  - Four stance-phase hip velocity target values
  - Four stance-phase knee energy target values
- Evolve a single stride at a time
  - Multiple turning angles
The Turn Fitness Function

- Fitness function: \( f = [f_a, f_{\Delta \alpha}, f_c]^T \)
  - General accuracy
    - Body state variables other than yaw, yaw rate
    - Acceptable ranges for roll, roll rate
  - Turn angle accuracy
    - Achieve the desired change in yaw angle
  - Correctness
    - Correct number of footfalls, correct footfall sequence, no excessive leg spread

Turn Results

Roll vs. change in yaw for the turn.

Conical pendulum model for the turn.
Multiple-Stride Turning

Multi-stride turn in the CW direction.

The Running Jump

- Same state machine as the turn
- Control parameters (17):
  - hip angles, velocity biases, knee energy
- Evolved in stages
  - Stage 1: Jump
  - Stage 2: Landing

[Diagram showing the stages of the running jump]
Results

Summary

• Non-traditional solution approach for complex motions, bio-inspired system
  – Evolutionary optimization vs. traditional approaches
    • No simplifying assumptions required
    • Emergent, unanticipated solutions

• Future of robotics
  – Realization of biological abilities
  – Non-traditional, biologically-inspired solution approaches
Future Work for Quadruped

- More robust gallop solution
  - Uneven terrain, changing speeds, heading control, stability
- Real-time turn, running jump controllers
  - Transitions to/from galloping, control of heading, height
- Controller architecture
  - Simpler method for cyclic behaviors (e.g., neural oscillator)
  - Evolve sequence of primitives + parameters
- Evolve solutions in bio-inspired quadruped robot
  - Planar gallop + planar maneuvers
  - Simulation to hardware: Jumping the “reality gap”

Future Work

- Develop dynamic movements for biped
- 19 degree-of-freedom model (DOF) in RobotBuilder
  - 6 DOF legs
  - 3 DOF arms
  - 1 DOF waist axis