Skippy: Reaching for the Performance Envelope

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What is Skippy?

- a hopping and balancing machine
- an attempt to achieve far higher physical performance than today's robots
- an attempt to test the following hypothesis:

  *It is easier to increase the complexity of a high-performance robot than to increase the performance of a highly complex robot.*
What is Skippy?

(Speculation)

- Skippy
- Hard
- Descendants of Skippy
- Today's robots
- Harder
- Robots of tomorrow

Performance vs. Complexity
What is Skippy?

A robot that is/has

- fully autonomous — no umbilical or harness
- light weight — \(~2\text{kg}\)
- only 2 actuators — maximally simple
- energetic — 4m hop
- robust — crash land from 4m without damage
- versatile — balance, bow, swivel, hop, somersault, tumble, dance, pirouette, climb stairs, fall over and get back up again, . . . .
What is Skippy?

Why hopping and balancing?

1. because they are foundational skills for an athletic robot
2. because they enable many other skills
3. because they have very different (and conflicting) requirements, so the robot must be *versatile* if it is to be good at both

hopping needs explosive power
balancing needs exquisite control
Specification: Hopping

- Skippy must be able to hop 4m and land on its foot, or crash without damage.
- Up to 50% of the required energy can come from the previous hop.

Why 4m?
- because it's outrageous
- because it's spectacular
- because it's possible
- because it pushes the limits
- because it focuses attention on physical performance
Specification: Hopping

Some numbers:

- 2kg @ 4m = 80J
- 4m hop → 9m/s launch velocity
- 9m/s → 1.8s flight phase
- 9m/s @ 0.5m stroke
  → 0.2s stance phase (10% duty cycle)
  → 9g average stance acceleration
  → 200N average thrust
- if 40J from previous hop then
  → 200W average stance power
Specification: Hopping

Skippy must also be able to make

- small hops
- single hops
- hop sequences
- precisely targeted hops
- hops off inclined surfaces
- modified hops (somersaults, etc.)
Specification: Balancing

Skippy must be able to

- balance on a point in 3D
- balance while making large fast movements
- balance quickly on landing
- lean in preparation for a hop
- control all three posture angles
- control attitude during flight
- control foot placement on landing

(Skippy must also be able to get up by itself after a fall)
Normal Robotics Research

**Step 1:** create a robot that is
- very complex
- very expensive
- very fragile/self-destructive
- very heavy
- barely strong enough

**Step 2:** perform experiments
- very cautiously
- at low speeds
- hampered by complexity, risk management, frequent failures, repairs, poor performance, ....

The Skippy Approach

**Step 1:** create a robot that is
- maximally simple
- relatively cheap
- robust/non-self-destructive
- light
- highly energetic

**Step 2:** perform experiments
- aggressively
- safely at high speeds
- making rapid progress and discovering new things
Design: Mass Distribution

Mass distribution strongly affects performance. For good performance, the mass should be concentrated in the areas shown.
Design: Mass Distribution

excellent hopper
bad balancer

OK hopper
bad balancer

good hopper
good 2D balancer

good hopper
good 3D balancer

plus some mass at the foot for in-flight attitude control
A spring-loaded ankle joint is necessary to allow Skippy to control its momentum at lift-off.
Design: Springy Ankle

A hop is essentially a planar movement taking place in the robot's sagittal plane.

To control all three components of momentum in this plane using only a single actuator, it is necessary to divide the launch phase into a **thrust phase** and a **steering phase**.

**thrust phase:** the main motor is saturated and operating at maximum power

**steering phase:** the springy ankle allows the main motor to control the direction of ground reaction force
Design: Springy Ankle

During the thrust phase, the ankle *remains flexed*, and the ground reaction forces exert a *positive* moment about the CoM.
Design: Springy Ankle

During the thrust phase, the ankle remains flexed, and the ground reaction forces exert a positive moment about the CoM.

During the steering phase, the ankle extends, and the ground reaction forces exert a negative moment about the CoM.
Design: Nonlinear Springs

- High stiffness for high bandwidth
- Lower stiffness for high energy storage
Design: Nonlinear Springs

- Ankle spring
- Enough force for traction during steering phase
- Ankle sits here at end stop during thrust phase

Graph:
- $F$ vs $x$
- Ankle spring
Design: Energy Flows

![Graph showing energy flows over time with different energy components labeled.](image)
Spin-off: Ring Screw

The main limiting factor on Skippy's mechanical performance is the speed limit of the ball screw. This has led to the invention of the *ring screw*...
Spin-off: Ring Screw

Three rings mounted in bearings make theoretically perfect rolling contact with the screw rod. This mechanism performs the same function as a ball screw, but without the speed limit.
Results

Can Skippy really do everything with only two actuators? We have been working on this question, and now have several results.

Hopping:

- small single hops in 2D with a target landing point, beginning and ending in a balanced position, using only one actuator
  - controlled crouch and forward lean
  - controlled launch achieving accurately a desired dynamic state at lift-off
  - in-flight control of foot motion, and accurate foot placement on landing
  - recovery of balance after landing
Results

Balancing:

- quantitative measures of a robot's physical ability to balance
  - *guides and evaluates the design*

- a new model of the physical process of balancing
  - *leads to new and better control systems*

- high-performance balancing in 2D
  - *balance any planar mechanism, even with kinematic loops*
  - *use any combination of joint motions for balancing*
  - *perform large, fast movements without falling over*
  - *fast, accurate tracking by leaning in anticipation*

- bend-swivel balance control in 3D
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For more information: http://royfeatherstone.org/skippy/

THE END