Robot's Inner Ear:
Toward Humanoid Stabilization Using Only Inertial Sensors

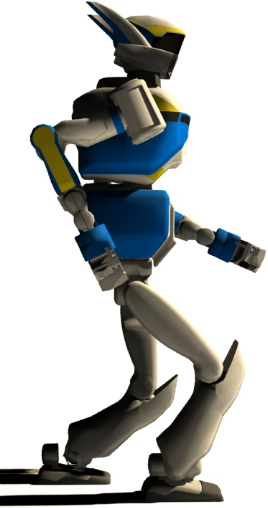
Mehdi Benallegue, Florent Lamiraux

Gepetto team - LAAS / CNRS
Toulouse, France

JNRH - 2014

HRP-2 walking

The dream



HRP-2 (36 Dof) walking control

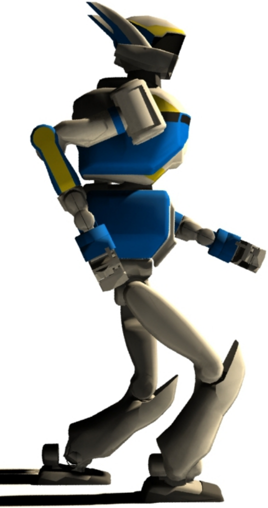
1. has to move the CoM to track a reference trajectory of the center of pressure (CoP)
2. generates a 36 DoF motion to create ground reaction forces according to the obtained reference.

But it assumes:

- flat horizontal ground
- no external perturbations.
- rigid joints and links

HRP-2 walking

The reality



What actually happens:

- uneven ground
- presence of perturbations (unexpected external forces).
- modeling errors (in kinematics and dynamics)
- the foot-ankle link of HRP-2:
  - has rigid ankle joints and flat soles, but
  - flexible material between the sole and the ankle (for impact absorbing)
  - moves the whole robot when excited.

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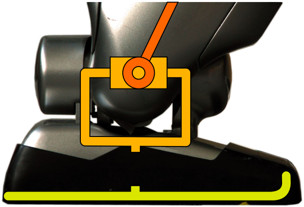

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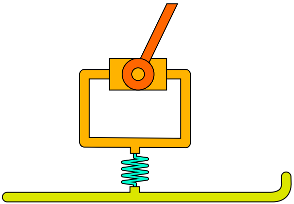

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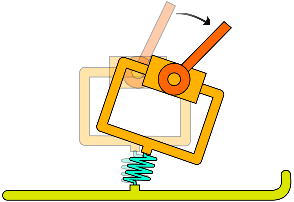

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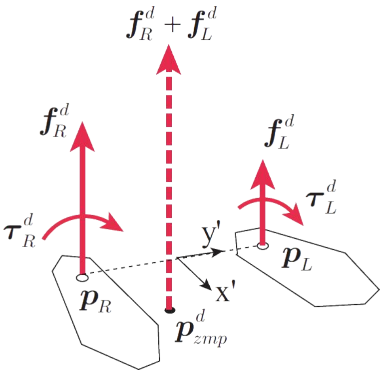
Current solutions



- Use mostly the force/torque sensors under the sole of the robot to respect CoP
  - Requires good modeling of the robot's dynamics and flexibility
  - Depends on very precise sensors calibration
- Cannot be adapted to robots without these sensors
- Don't consider other sensors embedded on the robot.
- IMU sensors are used only for reconstructing the attitude of the upper-body
- Humans can walk without tactile or position sense in the foot.

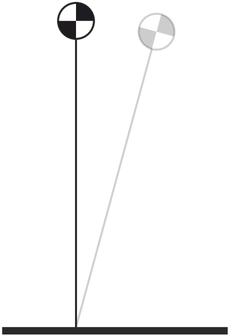
Our objective

Using only IMU measurements, our objective is to:

- Take into account perturbations on the robot
  - Flexibility of joints and limbs
  - Small modeling errors
  - External perturbations
- Reconstruct and track the perturbations in real time using embedded sensors.
- Correct the CoM trajectories to ensure balance.
- Use contact points information.

Toy example

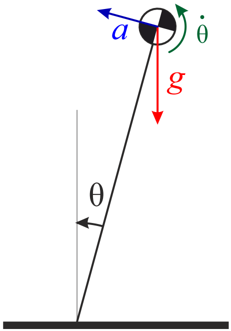
Inverted pendulum



An inverted pendulum of length h with an IMU on the top of it.

Toy example

Inverted pendulum

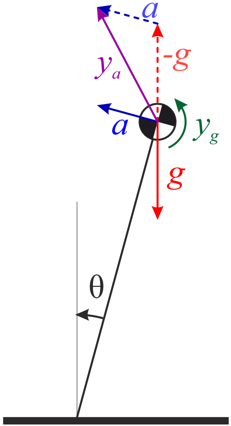


Its kinematics:

- an angle θ between the orientation of the pendulum and the gravity g direction,
- an angular velocity $\dot{\theta}$,
- an angular acceleration $\ddot{\theta}$, related to a linear acceleration $a = h\ddot{\theta}$

Toy example

Inverted pendulum



The IMU:

- an accelerometer which measures y_a, let's suppose centripetal acceleration negligible, even if this doesn't change anything, $y_a = a - g$
- a gyrometer which gives $y_g = \dot{\theta}$

Toy example

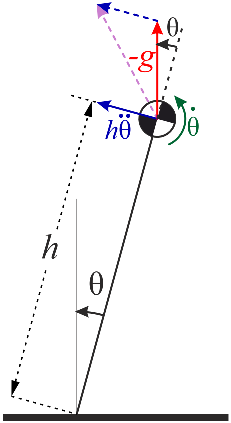
Inverted pendulum

Using only the imu:

- an approximate estimtaion of the gravity field (linear accelerations are considered noise)
- no measurement of the position
- no estimation of the accelerations

Toy example

Inverted pendulum



Using also the contact position:

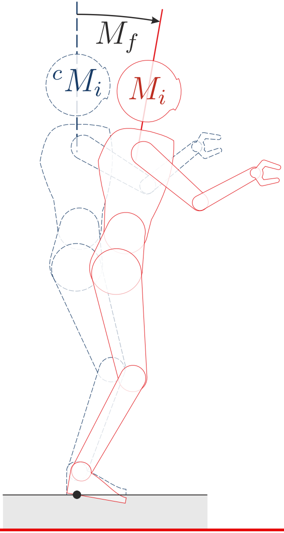
- we have access to orientation with two derivation orders,
- we know also the space position, velocity and acceleration.

Back to the robot: Perturbations model

rigid hypothesis

Our model is:

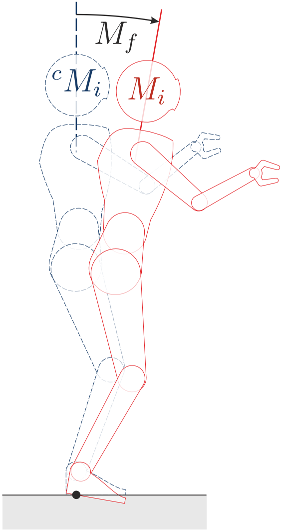
- The robot is rigid
- The perturbation is only an isometric transformation M_f:
    - the controller knows the position of any robot's limb i in the local frame ${}^c\mathbf{p}_i$
    - its position M_i in the global frame may be different,
    - $\mathbf{p}_i = M_f {}^c\mathbf{p}_i$
- Contact points j are approximately fixed to the ground (${}^c\mathbf{p}_j \approx M_f {}^c\mathbf{p}_j$)
- We observe the state $x = (M_f, \dot{M}_f, \ddot{M}_f)$



Flexibility dynamical system

state and measurements

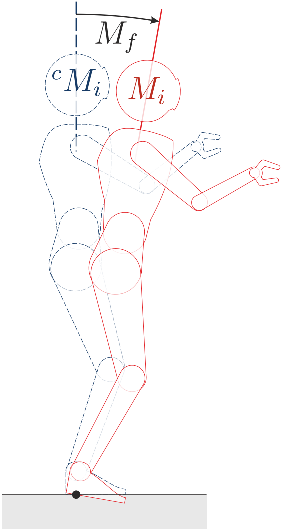
- We can have any model of flexibility:
  - response to deformation (e.g. linear or nonlinear spring)
  - model of external forces
- For proof of concept, we only consider constant $\ddot{M}_f$
  - the state dynamics is a simple double integrator
  - no model of the response of the actual flexibility.
- The IMU measurements depend on:
  - the desired position, velocity and acceleration of the IMU in the local frame $x = (M_{imu}, \dot{M}_{imu}, \ddot{M}_{imu})$
  - the flexibility state $x = (M_f, \dot{M}_f, \ddot{M}_f)$



Flexibility observation

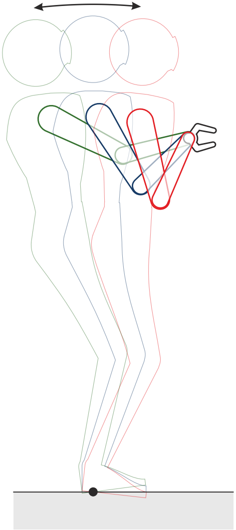
Extended Kalman filtering

- We use an Extended Kalman Filter.
- Correct the wrong predicted state with IMU measurements
- We add fake measurements telling that the contact points positions are constant.
  - changing the noise covariance changes the stiffness of this constraint.
  - with at least one contact, this translations and rotations become coupled.
- Everything is observable except:
  - the position and linear velocity (when no contact)
  - the yaw angle (when less than two contacts)
  - angular accelerations



Demonstration

robot hand compensation



- The robot hand has a reference position $M_{h,r}$
- The flexibility M_f is estimated.
- The reference position for the controller is then ${}^cM_{h,r} = M_f^{-1} M_{h,r}$
- The robot is perturbed with external forces.
- The robot moves but keeps the hand in the same position.

Video

Stabilization

first approach

- The CoM has to be stabilized to guarantee robot's balance.
- The flexibility is decoupled into lateral and frontal components.
- A rough model of the flexibility as a linear spring, linearized around rest position
- A simple pole placement is used for the CoM actuation.
- The double support is also taken into account.
- The angular momentum is reduced by keeping upright position of the Torso.

Video (simulation)

Conclusion

- Demonstration of a perturbation reconstruction and stabilization with only IMU measurements.
  - Will provide robots with no force sensor with a reliable stabilizer.
  - Will give redundancy for other robots to improve robustness to other kinds of perturbations (uneven ground, external forces)
- Enables to explore the potential importance of human's vestibular system to keep balance.

What's next?

- Finish the control of the stabilization
- Improve the model of flexibility
- Integrate other sensors
- Extend the model to ground perturbations
- Integrate the full dynamical model of the robot
- Use more robust controllers (model preview controllers for example)

Thank you!