A computational model for trajectory planning and on-line movement control in rhythmic tasks

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Introduction

A simplified juggling task was controlled either through a continuous rhythmic movement, or through a train of discrete movements, depending on the task tempo. Here we present a computational model of this task, aiming at producing PLANNED discrete movements at slow tempo and rhythmic movements at fast tempo. Our key hypothesis is that the rhythmic output corresponds to a simpler (and non-rhythmic) input than the discrete output, as suggested by the Central Pattern Generator paradigm. In addition, we aim at including the bimanual coordination rules into our model.

Conclusion

- The rhythmic and discrete control modes realize similar closed-loop control of the puck energy.
- They balance differently the trade-off between performance (control energy) and robustness (acceleration at impact).
- The single arm model produces both rhythmic movements (in-phase or anti-phase) with a constant tonic input, and discrete movements with a planned input, on the basis of an inverse model.
- A bimanual model of the task qualitatively reproduces the data, each control mode performing better at its own range of tempo.

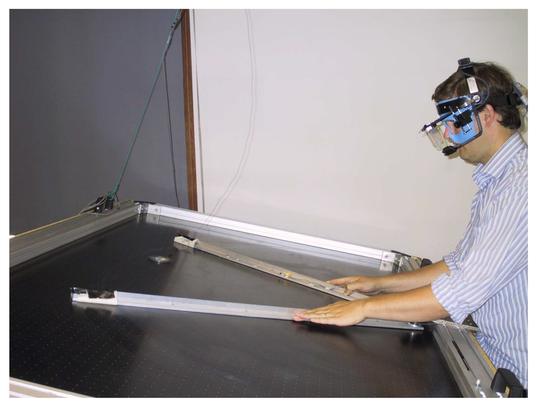
Methods

Nine human subjects participated in an impact juggling task. They rotated two edges to stabilize a flying puck along a period-one pattern. Puck, edges and head position were measured with an OptoTrak. Eye position with a Chronos Eye Tracker.

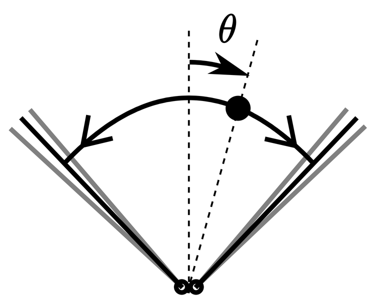
A computational model of the task has been implemented with Matlab and Simulink.

Measured position:
- head
- eye
- edges
- puck

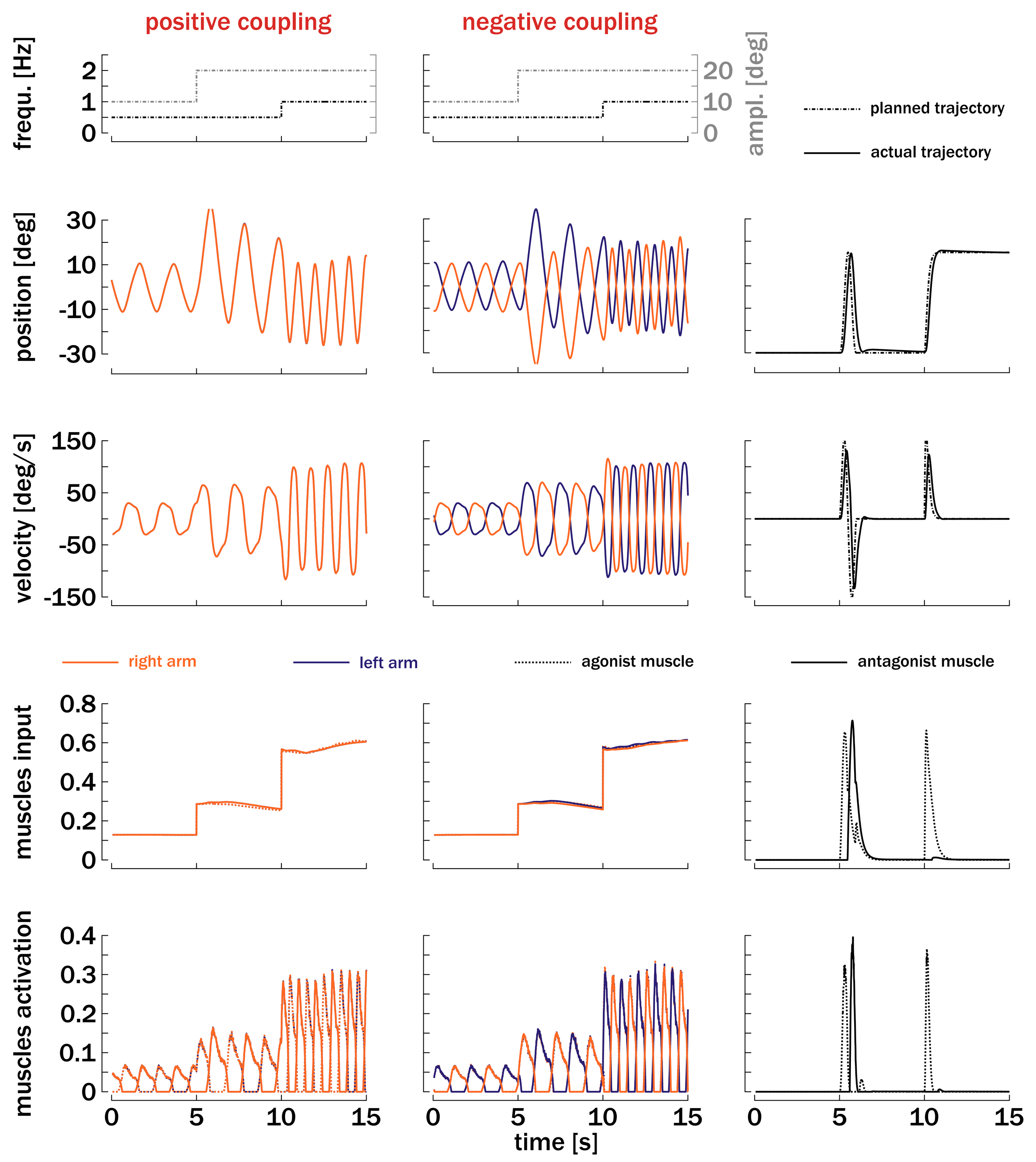
Conditions:
- metronom at 400ms
- metronom at 600ms
- metronom at 800ms
- metronom at 1000ms



WIPER robot



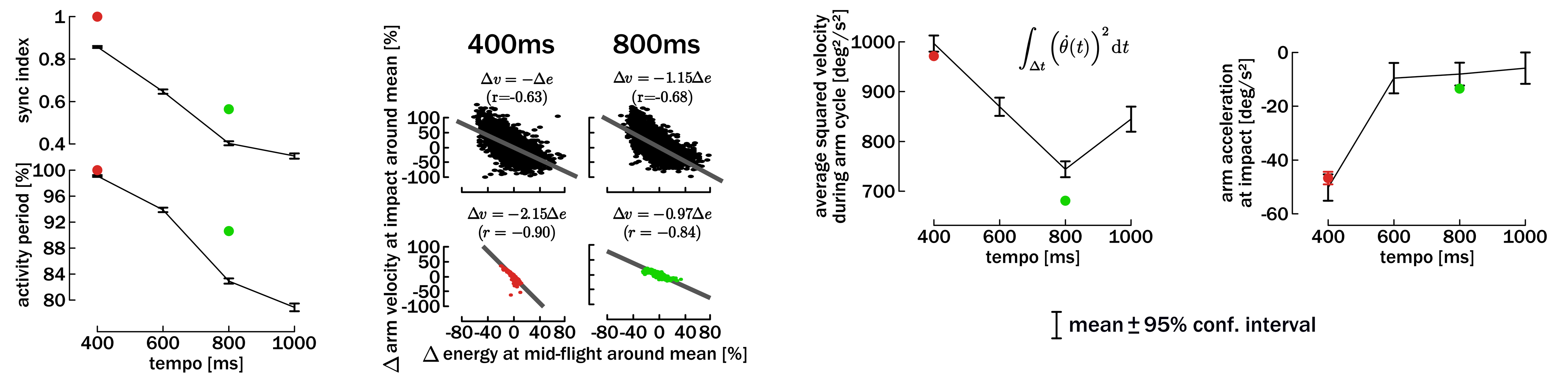
Modes of the model



The rhythmic movements correspond to constant inputs.
The discrete movements correspond to planned complex inputs.

Experimental data

(1) bimanual coordination — (2) closed-loop energy control — (3) trade-off between cheap and robust control



ACTIVITY condition:
velocity OR accel. crit.: $\dot\theta > 5°/s$ or $\ddot\theta > 20°/s^2$

SYNC index:

$$\cos\phi = \frac{\langle v_l, v_r\rangle}{\sqrt{|v_l|^2 \cdot |v_r|^2}} = \frac{\sum (v_l[k] \cdot v_r[k])}{\sqrt{\sum (v_l[k])^2 \cdot \sum (v_r[k])^2}}$$

(1) Depending on the tempo, the actuation was either a single *rhythmic* movement, sync between the arms (fast tempo - ●) or a train of decoupled *discrete* movements (slow tempo - ●).

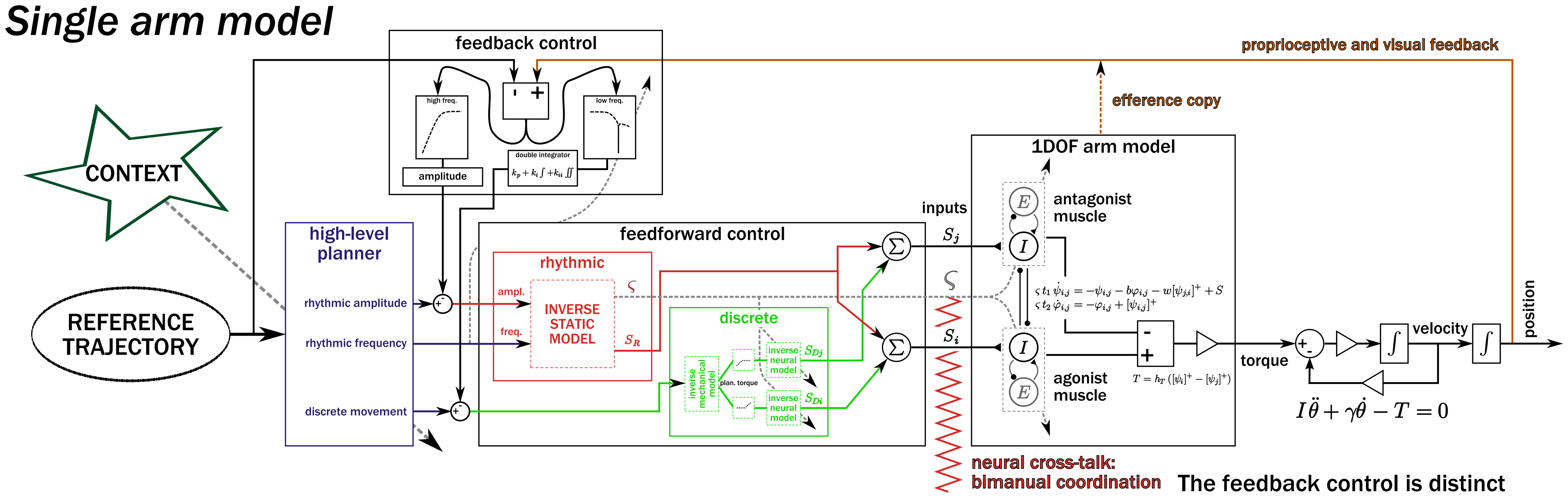
(2) The puck energy was closed-loop controlled whatever the actuation mode.

(3) The energy expense was reduced in the discrete actuation mode.
In contrast, the rhythmic mode stabilized a *negative* arm acceleration at impact, i.e. a necessary condition of *robustness*.

The matching between actual and simulated data is good.
The "rhythmic" gain is higher in the model.

References: Schaal et al., Journal of Motor Behavior (1996); Sternad et al., Physical Review E (2001); Ronsse et al., IEEE Transactions on Robotics (2006, cond. accepted)

Single arm model



The arm model consists in two mutually inhibitory neural circuits (inhibitor + adaptation). They drive two antagonist muscles, producing the positive and negative torques.
For a common constant input, the model oscillates at a frequency depending on the time constant of the neural leaky integrators.

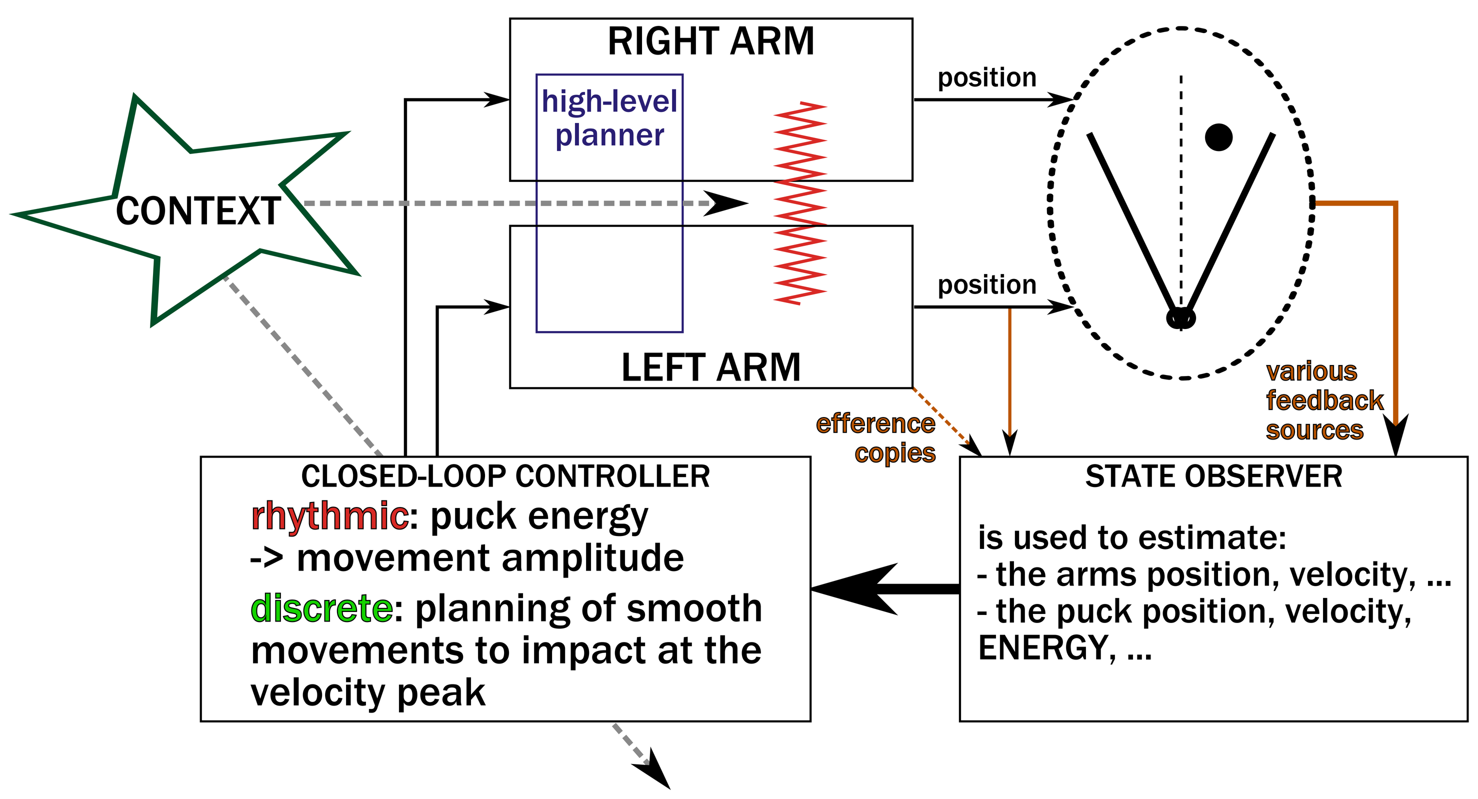
Due to the particular structure of the arm model, an inverse model for trajectory PLANNING can be constructed on the separation of positive and negative planned torques.
The rhythmic and discrete primitives can be consequently combined.

The feedback control is distinct for low and high frequencies.
The low frequencies are stabilized by a classical PI controller.
The rhythmic amplitude is controlled through high frequencies.

The context determines rhythmic or discrete planning.

References: Matsuoka, Biological Cybernetics (1985, 1987); Sternad et al., Human Movement Science (2000); de Rugy and Sternad, Brain Research (2003)

Task model



Depending on the context, the model relies either on the rhythmic or on the discrete mode.
The rhythmic mode has larger bandwidth and robustness. The feedback is simply implemented by tuning the amplitude on the basis of the measured puck energy.
The discrete controller plans smooth trajectories to impact the puck at the velocity peak and steady-state angle. The impact velocity is calculated to stabilize both the puck energy and the phase between the two arms.
The rhythmic controller is adopted at the fastest tempo and the discrete controller at the slowest one.