Incremental Learning in Physical Human-Robot Interaction Using Predicting Coding-inspired Variational RNNs

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1. Abstract

Advancing Human-Robot Interaction (HRI) requires robots to learn and adapt from human guidance in ways that mimic human cognitive processes. This study introduces a novel approach using a Predictive Coding-inspired Recurrent Neural Network (PV-RNN) [1] based on the Free Energy Principle (FEP) [2]. We explore the network's ability to generate novel creative movements through incremental learning from human interaction.

2. Neuro-Robotics Setup

Current study uses a humanoid robot with 16 DoF torso, Torobo to conduct HRI experiments. Unique feature of Torobo is that it is equipped with a built-in force-feedback controller enabling human to back-drive joint angles with subtle force.

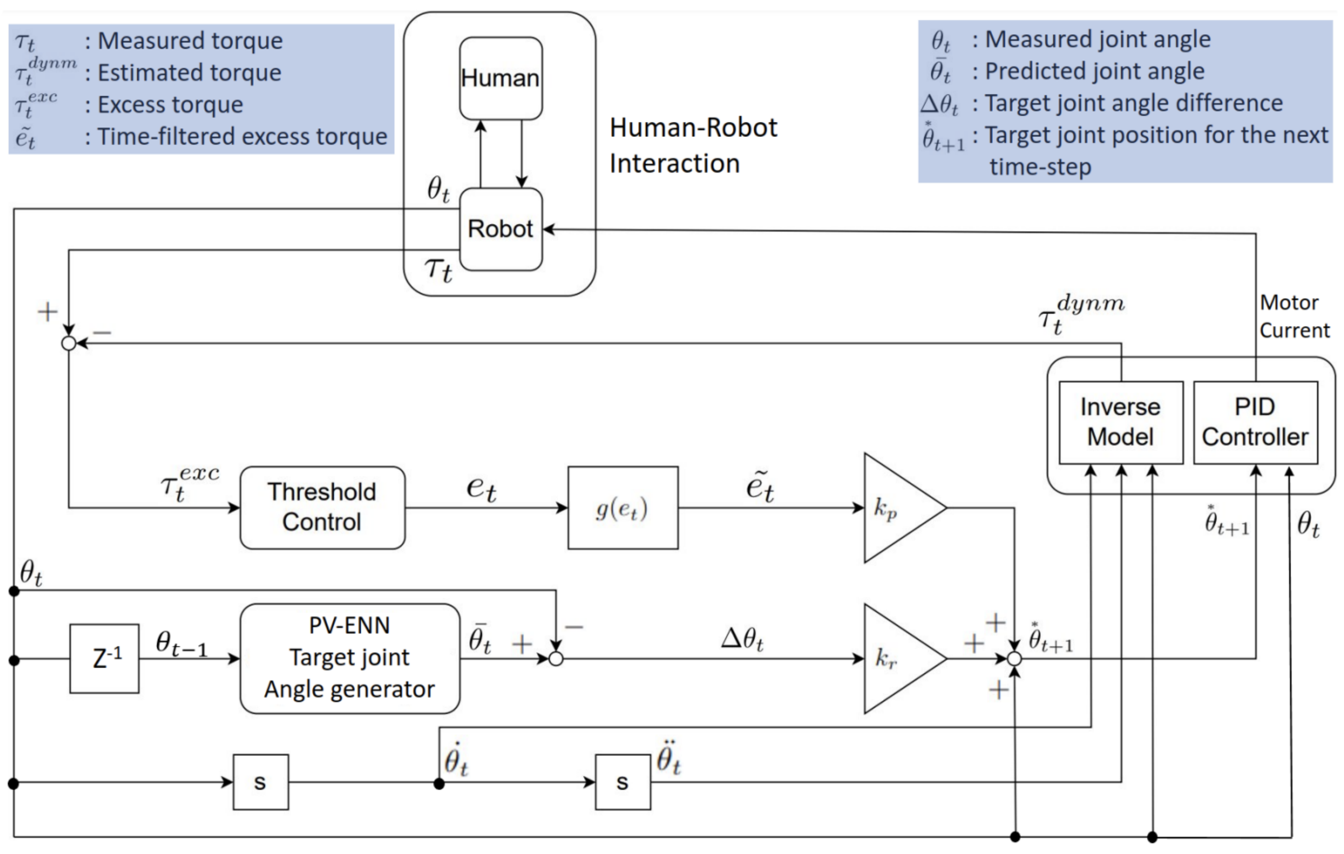

Fig.1 Neuro-Robotic Setup of HRI [3]

3. Free Energy Principle

Free Energy Principle (FEP) is a theory suggesting that the brain reduces uncertainty by predicting sensory inputs and continuously updating its internal models.

$$\mathcal{F} = \underbrace{D_{\mathrm{KL}}[q_\phi(\boldsymbol{z}|\boldsymbol{X})\|p_\theta(\boldsymbol{z})]}_{\text{complexity}} - \underbrace{\mathbb{E}_{q_\phi(\boldsymbol{z}|\boldsymbol{X})}[\log p_\theta(\boldsymbol{X}|\boldsymbol{z})]}_{\text{accuracy}},$$

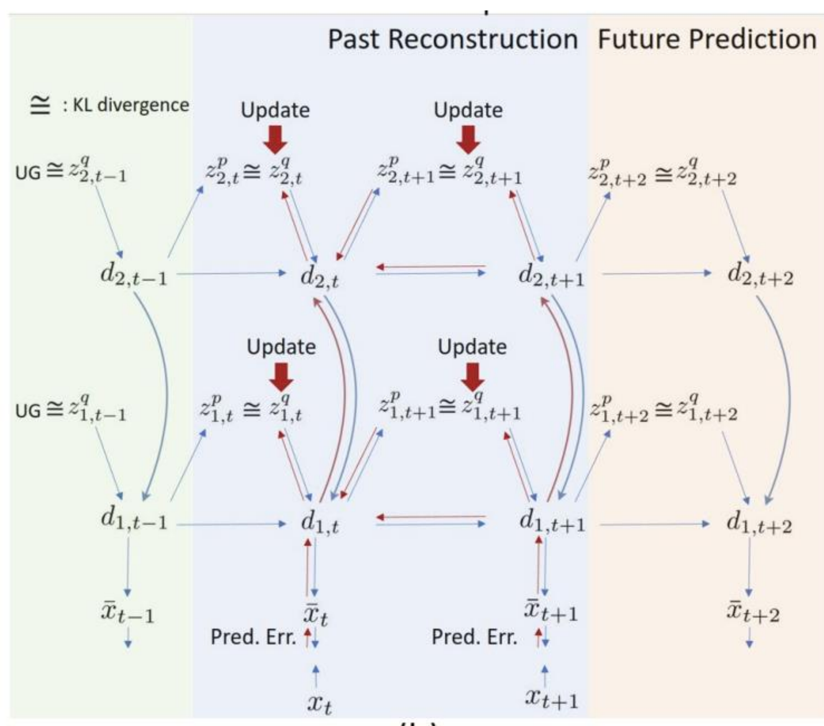

Fig.2 PV-RNN Structure [3]

4. PV-RNN

Predictive Coding-inspired Variational RNN, PV-RNN, is built based on FEP, having the weighted Free Energy as a loss function:

$$\mathcal{F}^{train} = w\sum_{t=1}^{T-1}\mathbb{E}\big[\underbrace{D_{\mathrm{KL}}\left[q_\phi(\mathbf{z}_{t+1}|\mathbf{d}_t,\mathbf{X}_{t+1:T+1})\|p_\theta(\mathbf{z}_{t+1}|\mathbf{d}_t)\right]}_{\text{complexity}}\big] - \underbrace{\sum_{t=1}^{T}\mathbb{E}[\ln p_\theta(\mathbf{X}_t|\mathbf{d}_t)]}_{\text{accuracy}},$$

Adjusting meta-prior *w* varies the network's characteristics from rigid to easily modifiable.

5. Experiment

PV-RNN was initially trained on four different movement primitives and incrementally trained up to nine through five teaching session. In each session, a human physically held Torobo's hands when it generated movements from the existing PV-RNN model, in a way it reinforces pre-learned movements or guides the robot to learn a new movement. One new movement was added per session, resulting in nine movement primitives taught.

6. Result

- The results demonstrated that the PV-RNN, guided by the Free Energy Principle, can integrate up to nine different movement patterns through repeated human interaction without showing immediate signs of memory saturation or interface.
- As more patterns were learnt, a "blurring" effect emerged – movement became less distinct and more variable.
- Through physical interaction, for lower meta-priot *w*, each movement's learning and generating became more indistinct from other movements.

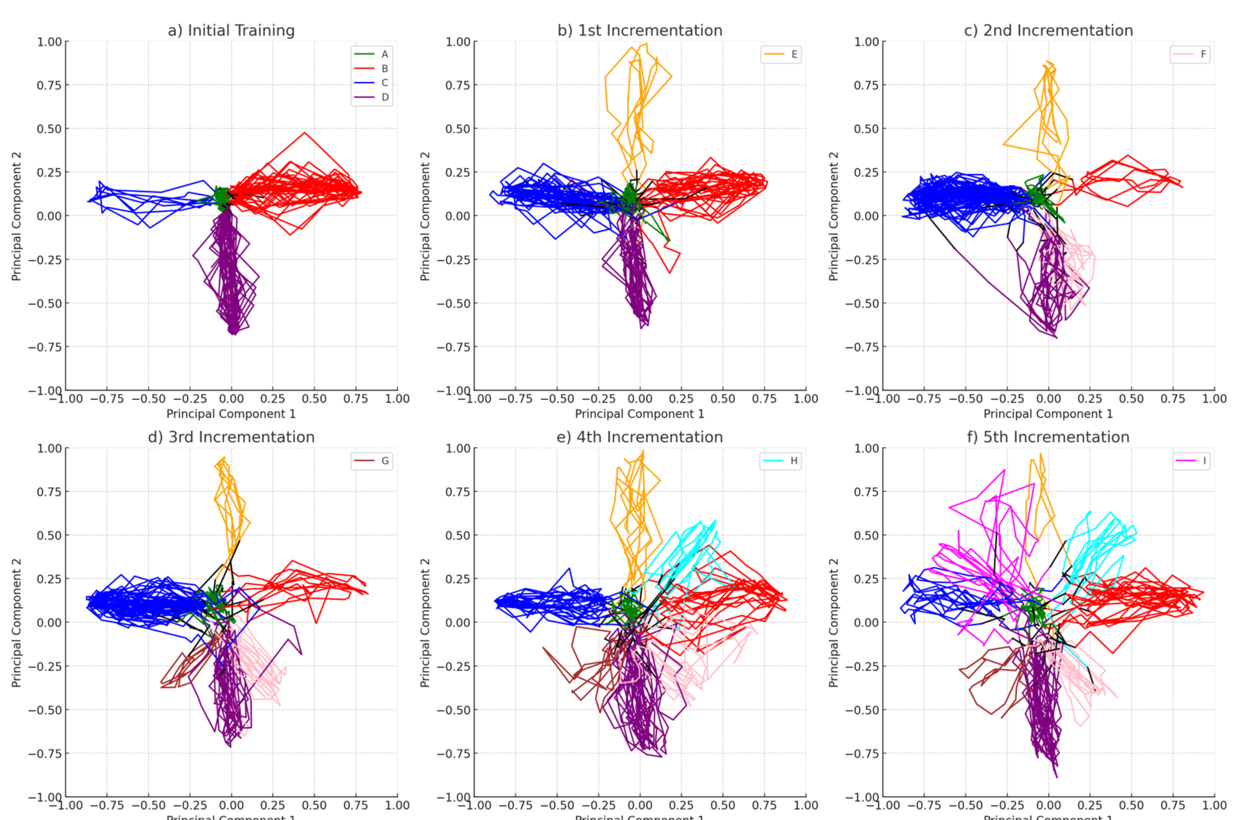

Fig.3 PCA result of the generated trajectories after each training session

7. Discussion

- PCA analysis suggests that learning additional patterns could eventually lead to mixing, possibly fostering the emergence of new movement patterns.
- The potential for memory saturation leading to creative pattern formation parallels human cognition, where blending learned experiences can generate new ideas or actions.
- As an extending study, we are going to teach the robot with more diverse movements such as different frequencies.

[1] Karl Friston. A theory of cortical response. *Philosophical transactions of the Royal Society B: Biological sciences*, 360(1456): 815-836, 2005.
[2] Ahmadreza Ahmadi and Jun Tani. A novel predictive-coding-inspired variational rnn model for online prediction and recognition. *Neural computation*, 31(11):2025-2074, 2019.
[3] Sawada, Hiroki, Wataru Ohata, and Jun Tani."Human-robot kinaesthetic interaction based on free energy principle." arXiv preprint arXiv:2303.15213 (2023).

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