Integration and Continual Learning-Based Modeling of a Soft Robotic Sensor for Social Robot Proprioception

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Background and Motivation

Children interacting with social robots expect safe, natural, and expressive motion. HARU, a tabletop robot for child–robot interaction, needs a neck that feels lifelike yet remains safe.

HARU uses Soft Continuum Actuators (SCA) for improved safety and expressivity. However, soft actuators inherently lack reliable proprioceptive feedback which is essential for closed-loop control.

Our goal is to embed strain sensors directly into the SCA neck structure without altering its compliance or appearance, and map sensor signals to accurate orientation estimates in real time.

Application and Goals

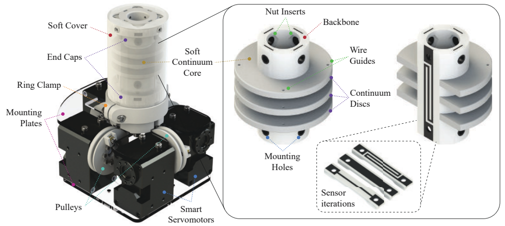
HARU is a tabletop social robot developed for child robot interaction. Recent prototypes replaced HARU's rigid neck and eye joints with Soft Continuum Actuators (SCAs) to improve safety and expressivity during interaction with children.

Smart Soft Continuum Actuator (SSCA): An SCA with embedded strain sensors and learning-based proprioception for real-time pitch and roll estimation without external tracking.

Platform & Sensor Design

The SSCA serves as the compliant neck joint for the social robot HARU. This soft design replaces previous rigid joints to ensure safer and more expressive child-robot interactions.

The SSCA's motion is defined by a central, cylindrical continuum core. Three spacer discs are distributed along this backbone to provide structural support and act as guides for the internal wiring.

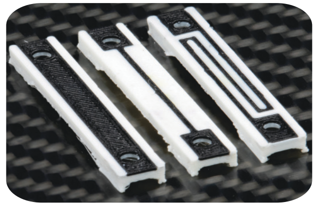


The sensors are arranged in an orthogonal cross-configuration. This specific layout allows the system to capture the actuator's two dominant degrees of freedom: pitch (θ) and roll (ψ)

Fabrication

Materials: Non-conductive TPU (Shore 85A) for the structural continuum backbone; conductive TPU (Shore 90A) for the sensing traces.

Method: A Single-step multi-material FDM printing with 90% infill, 0.1 mm layer height.



Four gauge-pattern sensors are integrated radially in a cross-configuration to measure both pitch and roll independently.

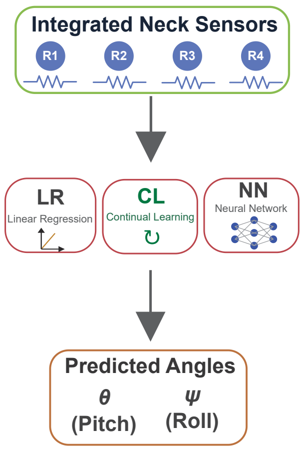
Sensor Geometries Evaluated:

Linear (5 mm width): R^2 θ = 0.90, R^2 ψ = 0.32

Linear (1 mm width): R^2 θ = 0.75, R^2 ψ = 0.50

Gauge pattern (selected): With R^2 θ = 0.94, R^2 ψ = 0.79, this provides best linearity and repeatability due to distributed conductive path that increases effective strain under bending.

Learning-Based Proprioception



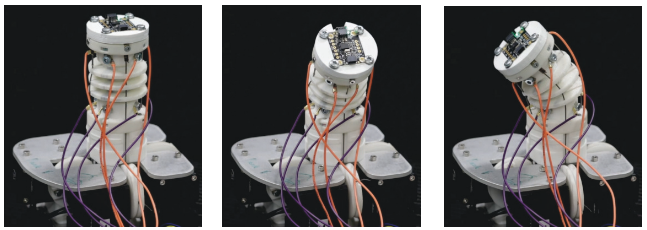
Sensor resistances are mapped to pitch (θ) and roll (ψ) orientation estimates using three models:

1. Linear Regression (LR): Baseline model; fast but limited by sensor nonlinearity and drift.

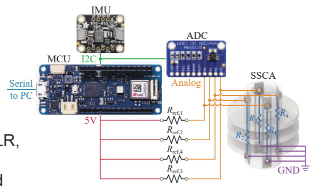
2. Static Neural Network (NN): Feedforward network captures nonlinear behaviour, however the parameters are fixed after training.

3. Continual Learning (CL): Parameters update online during operation to adapt to drift and material changes over time. This allows the model to adapt to sensor drift and material changes during long-term operation

Implementation and Training

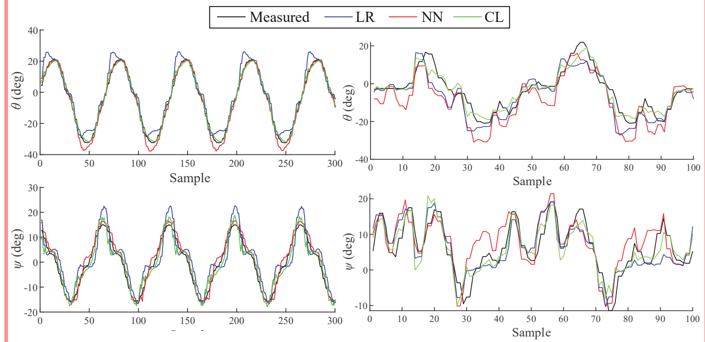


The SSCA was evaluated under five predefined motion profiles: circular, rectangular, diagonal, pitch-only, and roll-only, plus high-frequency randomized motions.



- Four embedded neck sensors arranged in a cross-configuration
- Three learning approaches were evaluated: LR, NN, and CL
- Evaluated across predefined and randomized trajectories

Results



Robust under Repeated Motion

Robust under randomized motion

R^2 > 0.97
MAE < 1°

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