# Designing Comfortable Robotic System with Human Comfort Analysis and Modeling in Human-Robot Collaboration

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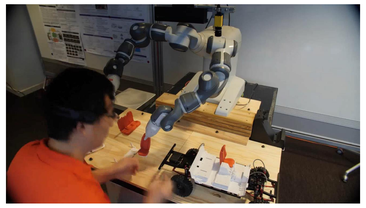
## Problem Statement

- One of the limitations of the HRC studies is the lack of emphasis on human comfort, which is critical to the user acceptance of COBOTs and human experience during the HRC tasks.
- Existed comfort evaluation methods merely use subjective ratings or simple statistical comparison approaches. There is a lack of a mathematical modeling approach to evaluate human comfort in HRC tasks.
- The goal of this study is to build individual human comfort models with analytical and machine learning approaches.



## Experimental Comfort Studies and Modeling in HRC

### Experimental Comfort Studies

- Robot behavior variations in HRC

| Factors / Levels | Distance (cm) | Robot Speed | Height (cm) | Approach Trajectory | Delivery Pose |
|---|---|---|---|---|---|
| 1 | 25 | 0.1 | 15 | Straight | Flat |
| 2 | 37.5 | 0.2 | 30 | Left Curve | Vertical |
| 3 | 50 | 0.3 | 45 | Right Curve | |
| 4 | 62.5 | 0.4 | | | |
| 5 | 75 | 0.5 | | | |

- Humans provided comfort levels by a force pressing device and speech.
- Physiological data were collected using wearable devices.
- Empatica E4 wristband was used to record in-situ heart rate (HR), Electrodermal Activity (EDA), Blood Volume Pulse (BVP) and skin temperature data.
- Emotiv EpocX headset was used to record in-situ EEG data.

### Analytic Comfort Modeling

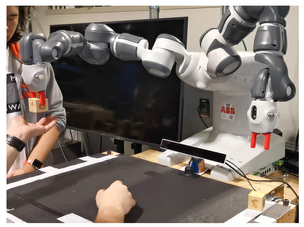
- Human comfort is modeled based on primitive comfort factors determined by robot behaviors

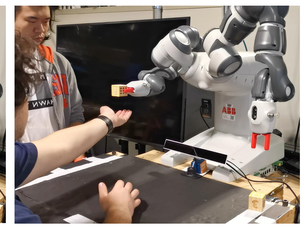
$$L(\alpha) = \frac{1}{M}\sum_{i=1}^{M}(R_i - \alpha^T \tilde{r}_i) \quad R(r_i) = \sum_{j=1}^{N}\alpha_j r_{ij} + \alpha_0$$

### Physiological Comfort Modeling

- Human comfort is identified based on in-situ physiological signals
- A multi-class error-correcting output codes SVM (ECOC-SVM) approach is employed to classify the comfort levels.
- Three different techniques including Independent Component Analysis (ICA), Support Vector Machine Recursive Feature Elimination (SVMRFE) and Autoencoder were implemented independently for feature selection.

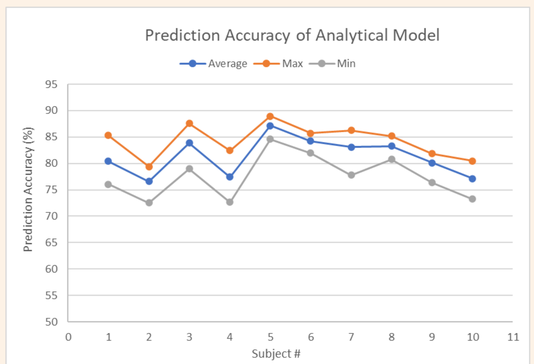






## Validations & Results

### Analytical Comfort Model Prediction Results




- The overall average accuracy of analytical model among all participants is 81.33%,
- The overall maximum accuracy is 88.94%, and the overall minimum accuracy is 72.53%.
- The highest average accuracy result is 87.13%, while the lowest average accuracy is 76.59%.

| Delivery Distance (cm) | Primitive Comfort Reward |
|---|---|
| 25 | 0.575 |
| 37.5 | 0.658 |
| 50 | 0.433 |
| 62.5 | 0.044 |
| 75 | -0.209 |

| Robot Speed | Primitive Comfort Reward |
|---|---|
| 0.1 | -0.127 |
| 0.2 | 0.240 |
| 0.3 | 0.547 |
| 0.4 | 0.496 |
| 0.5 | 0.44 |

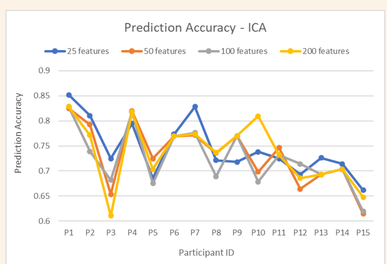
| Delivery Height (cm) | Primitive Comfort Reward |
|---|---|
| 15 | 0.373 |
| 30 | 0.279 |
| 45 | 0.067 |

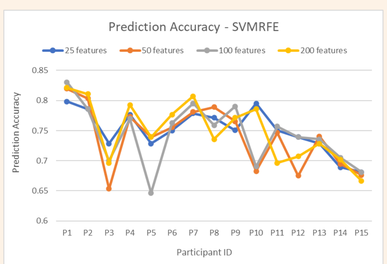
| Trajectory | Primitive Comfort Reward |
|---|---|
| Straight | 0.310 |
| Left Curve | 0.275 |
| Right Curve | 0.236 |

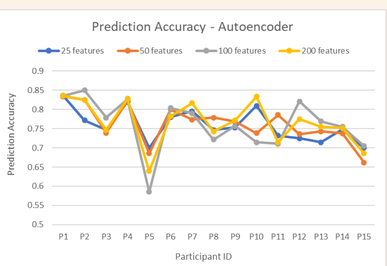
| Delivery Pose | Primitive Comfort Reward |
|---|---|
| Flat | 0.182 |
| Vertical | 0.142 |

- The factor analysis results indicate that robot behaviors do affect human comfort in HRC. Too long distance, too slow robot speed and too high robot pose yield high discomfort.

### Physiological Comfort Model Prediction Prediction



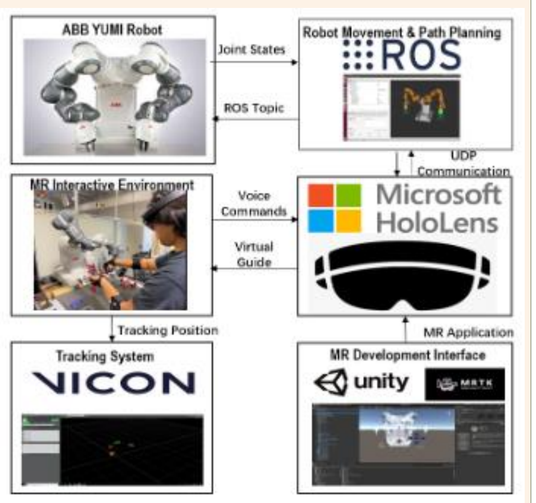




- The overall comfort level prediction accuracy of the ECOC-SVM multiclass classifier was 74.44%, 75.01% and 76.68% for the ICA, SVMRFE and Autoencoder feature selection methods respectively.
- The best accuracy of comfort level prediction among all participants was 92.86% with Autoencoder method and 200 extracted features option were applied.

## Ongoing Work

- Use the comfort model to guide the robot behaviors during human-robot collaboration system
- The guidance is also used to assist humans via mixed reality glasses




This work was supported by the National Science Foundation under Grant IIS-1845779.