Hand Movement Prediction based Collision-free Human-Robot Interaction

Yiwei Wang[†], Xin Ye[†], Yezhou Yang, Wenlong Zhang
Arizona State University
Arizona, USA
{yiwei.wang.3, xinye1, yz.yang, wenlong.zhang}@asu.edu *

1. INTRODUCTION

Modern household and factory robots need to conduct collaborative manipulation with human users and workers [2]. However, with the human in the loop, the robot controller has to take the human motion into consideration while planning an optimal trajectory to avoid collision and ensure safety. Therefore, two major capabilities should be involved in developing the robot controller: 1) a perception module that can track and predict the collaborator's movement, 2) an adaptive trajectory planning module that takes into consideration of the movement prediction and adjusts the robot manipulation trajectories. Moreover, these two capabilities need to be integrated seamlessly to enable real-time motion adaptation.

In this paper, inspired by the recent work of [1], we aim at predicting human collaborator's hand movement from visual signal solely. We adopt the Recurrent Neural Network architecture to enable a learning subsystem that learns the spatial-temporal relationships between the hand manipulation appearance with its next several steps of movements. To validate the effectiveness of the approach, we conduct experiments on both publicly available and new collected dataset which with readings from motion capture system to serve as the ground truth.

On the other side, we also propose a hand movement prediction based robot trajectory planning approach to reach its final destination and avoid collision. We validate this proposed method both in simulations and on an actual robot.

The main contributions of this paper are as follows: 1) we propose a perception module that takes in visual data solely and predicts human collaborator's hand movement. 2) we propose a new robot trajectory adaptive planning module that takes the noisy movement prediction signal into consideration for optimization. 3) we integrate a robot system that can collaborate with human workers on a set of trained manipulation actions, and we show it improves safety compared to a robot system without movement prediction. 4) we also collect a new human manipulation dataset that can supplement previous publicly available dataset with motion capture data to serve as hand location ground truth. We will make the new dataset available for future research. 5) We verify the effectiveness of the proposed motion prediction and robot trajectory planning approaches in experiments.

2. Our Approach

2.1. Visual Movement Prediction

The goal of the proposed vision submodule is to predict human hand movement from visual input. Here, we take the video frames achieved from the camera mounted on the robot as input, and we start by assuming that the human co-worker manipulates single object with one hand on a working plane.

To represent the hand movement from current frame to the next time step, we adopt a displacement measure (dx, dy), which is at pixel level. We adopt a CNN-RNN-based model from [1] to predict manipulation movement. The learning method includes a pre-trained Convolutional Neural Network (CNN) model, which serves as a preprocessing step to extract visual features from a patch of image input, and a Recurrent Neural Network (RNN) model is trained to predict hand movement (dx, dy). Here, we predict the next five steps of the human hand movement, namely $(d\hat{x}_1, d\hat{y}_1, ..., d\hat{x}_5, d\hat{y}_5)$, to assist the control submodule for planning a safer and smoother trajectory. Fig. 1 depicts the visual submodule.

2.2. Planning with Prediction

To generate a collision-free trajectory for robot manipulator, we propose a safety constraint that there should be a safe distance between human hand occupation and robot occupation, where the human hand occupation is computed based on the hand movement prediction. We add this constraint to the optimization problem proposed by [3]. By solving this optimization problem, we generate a collision-free trajectory.

*† indicates equal contribution.

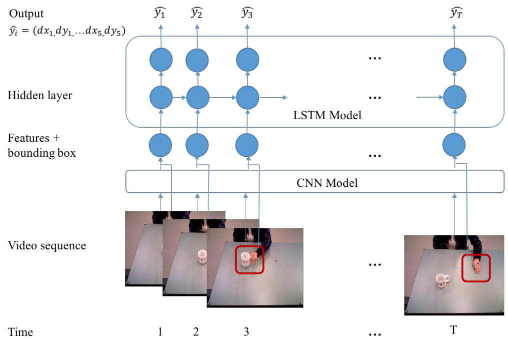


Figure 1: Hand movement prediction model

2.3. System Integration for Real-time Execution

Structure of the integrated system is demonstrated in Fig. 2, which enables real-time hand tracking, prediction and optimal collision-free trajectory generation.

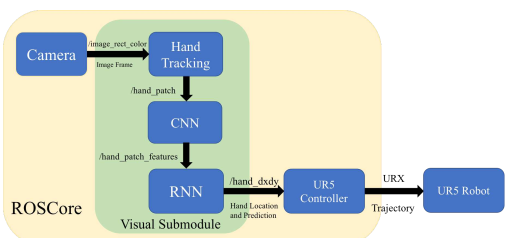


Figure 2: Structure of the entire system for safe HRI

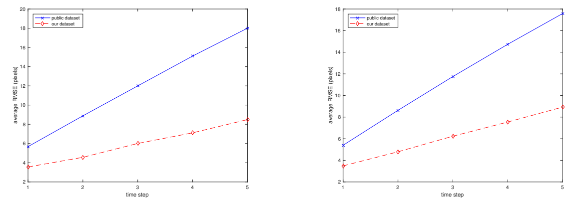
3. Experiments

Datasets: To validate the previous proposed hand movement prediction module, we conduct experiments on both publicly available and new data collected from our lab. Both datasets are human manipulation data of some subjects manipulating different objects with distinct actions, and each is repeated several times. Public dataset provides a total number of 625 recordings, while our new dataset complements 60 recordings with actual hand position in world coordinate by using motion capture system as well as the camera matrices, which can validate the movement prediction module.

Experiment I: Visual Movement Prediction

To evaluate the performance of our proposed movement prediction module, we adopt the widely accepted performance metric of RMSE. Here, RMSE is measured by the number of pixels. The total number of pixels is determined by the resolution of the video frames (640×480 pixels).

The training and testing protocol we used is leave-one-out cross-validation. On both testing beds, we report the average RMSEs as the performance of the trained models. Fig. 3 shows the RMSE performance. The experimental results demonstrate that our prediction module is able to predict human hand movement within an RMSE of about 18 pixels, which empirically validates our hypothesis a).



(a) Average RMSE of dx (b) Average RMSE of dy

Figure 3: Average RMSE of predicted hand displacements (dx, dy) from one step to five steps in the future.

Experiment II: Planning with Prediction

To validate the optimal trajectory generation method, we conducted a simulation test in Virtual Robot Experimentation Platform (V-REP). The simulation results demonstrate that trajectory generated with human motion prediction can avoid collision and guarantee safety.

Experiment III: An Integrated Robotic System

In this part, we conducted an experiment with a UR5 manipulator, a host PC and an Xtion PRO LIVE RGBD camera. A human co-worker was asked to perform the hammer pounding motion on the table, while the UR5's task is to move diagonally across the table while holding a cup of water. Fig. 4:LEFT shows a snapshot of the experimental setup. Fig. 4:RIGHT shows the trajectory of the robot end-effector, which successfully demonstrated a detour to avoid the human hand. This overall integration of the system empirically validates our hypothesis c).

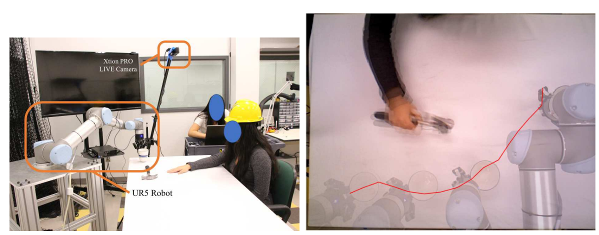


Figure 4: LEFT: Experiment setup; RIGHT: Experimental result: trajectory with safety constraint.

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