

Adaptive Environment-Aware Robotic Arm Reaching Based on a Bio-Inspired Neurodynamical Computational Framework

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Abstract—Bio-inspired robotic systems are capable of adaptive learning, scalable control, and efficient information processing. Enabling real-time decision-making for such systems is critical to respond to dynamic changes in the environment. We focus on dynamic target tracking in open areas using a robotic six-degree-of-freedom manipulator with a bird-eye view camera for visual feedback, and by deploying the Neurodynamical Computational Framework (NeuCF). NeuCF is a recently developed bio-inspired model for target tracking based on Dynamic Neural Fields and Stochastic Optimal Control theory. It has been trained for reaching actions on a planar surface toward localized visual beacons, and it can re-target or generate stop signals on the fly based on changes in the environment (e.g., a new target has emerged, or an existing one has been removed). We evaluated our system over various target-reaching scenarios. In all experiments, NeuCF had high end-effector positional accuracy, generated smooth trajectories, and provided reduced path lengths compared with a baseline cubic polynomial trajectory generator. In all, the developed system offers a robust and dynamic-aware robotic manipulation approach that affords real-time decision-making.

I. INTRODUCTION

Object manipulation is fundamental towards the integration of robots into the human-designed world. Several distinctive robotic manipulation works have been developed over the years employing humanoids (e.g., [1]), quadrupeds (e.g., [2], and soft robotics (e.g., [3]). To perform manipulation tasks effectively, robots must be able to understand their surrounding environment, localize available objects, and plan and execute accurate and adaptive reaching actions.

A growing number of studies seek to employ bio-inspiration for robotic manipulation [4]–[7]. Such methods aim to map the neural mechanisms underlying decision-making and motor control in humans and animals to support robot cognition [8]. In turn, human-like robot motion may also help provide a deeper understanding of the nature of human motor behavior [9], [10]. Thus, exploring bio-inspired methodologies and learning behaviors is important to develop and attain cognitive abilities in complex robotic applications.

Bio-inspired methodologies employed in robotics can be broadly split into three main categories; Spiking Neural Networks (SNNs), Liquid State Machines (LSMs), and Dynamic Neural Fields (DNFs). SNNs are activated by discrete events

called spikes or action potentials [11]. SNNs have been successfully deployed in 3D path planning [12] and direct robotic manipulator motion learning [13], and have served as internal models in reinforcement-learning-based target reaching training [14]. However, they remain limited in their applicability for real-time and dynamic decision-making, which can be crucial in many modern robotic applications. To this end, LSMs can lend themselves as a basis for more dynamic-aware bio-inspired methods. LSMs are based on reservoir computing [15], they contain a large number of recurrently connected neurons used to perform computations and recognize input patterns [16], and have been used in manipulation tasks [17], [18] in robotics.

Recently, DNFs have emerged as a prominent theory for real-time decision-making [19], and have been used to model aspects of perception [8], [20] and action [21]–[24] in both biological and non-biological systems. Several studies have applied the DNF theory in robotic reaching and grasping. Specifically, Ferreira *et al.* [25] presented a time-aware DNF-based control architecture for human-robot interaction, Strauss *et al.* [26] developed a DNF-based architecture for integrating visual input, decision-making, and motor planning in a robotic reaching task, and Knips *et al.* [27] proposed a neural dynamic architecture that utilizes DNFs for perception, movement generation, and action selection, enabling online updating of motor plans based on sensory feedback. While these approaches have made significant contributions to the field, they do not explicitly address the integration of optimal control principles for generating efficient reaching trajectories in the presence of multiple competing targets and uncertain states. Additionally, they do not provide a unified framework that can simulate a variety of motor tasks in dynamic environments, such as deciding between alternative options, stopping unwanted or inappropriate ongoing actions, and switching actions in response to environmental changes.

To address these limitations, we present the Neurodynamical Computational Framework (NeuCF), which merges DNF and SOC theory to generate adaptive reaching trajectories in a neurally plausible manner, integrating action selection, stopping, and switching mechanisms. NeuCF was designed and developed based on recent studies that modeled motor and the underpinning neural mechanisms in a variety of motor decisions performed by human subjects in dynamic and uncertain environments [28]–[30]. The architecture and parameters of NeuCF have been tuned based on reaching movements performed by human subjects in dynamic environments, ensuring biologically plausible behavior. Herein

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We gratefully acknowledge the support of NSF # CMMI-2133084, ONR # N00014-19-1-2264 and NINDS # U01NS132788. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding agencies.

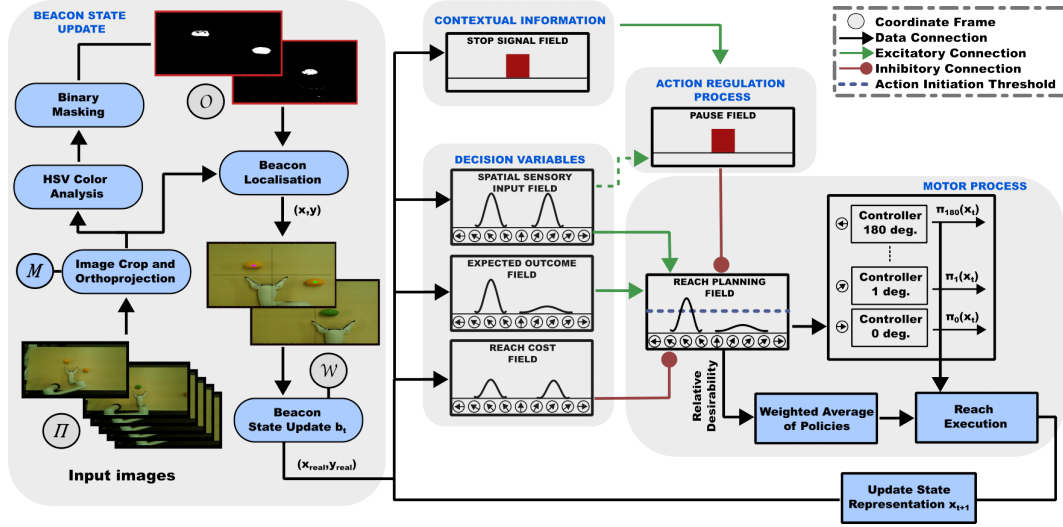


Fig. 1: NeuCF Model Architecture. The system receives images to compute beacon locations. The reach planning field encodes the planned direction of motion, integrating information from disparate sources. The relative desirability value for each action policy captures its attractiveness compared to alternatives and acts as a weight to compute the final action policy.

we focus on dynamic target tracking in open areas using a robotic six-degree-of-freedom manipulator with a bird-eye view camera for visual feedback. We present a robotic arm and camera-based system setup to evaluate the effectiveness of NeuCF in enabling robots to perform reaching tasks in dynamic environments with multiple competing targets.

II. MATERIALS AND METHODS

A. Neurodynamical Computational Framework (NeuCF)

In earlier work we have proposed a framework for action regulation tasks involving motor inhibition, such as selecting, stopping, and switching actions [29]–[31]. The framework integrates DNF with SOC, employing a network of DNFs to represent the neural circuitry responsible for various aspects of action regulation (including perception, expected outcome, effort cost, context signal, action planning, and execution) while allowing for the representation and selection of multiple potential targets. Optimal reaching strategies are created using SOC, based on the current environment state, and expected rewards and costs associated with each action.

Figure 1 illustrates the overall model architecture of our system. The neurodynamical framework receives image inputs from the camera to compute the beacon locations. Within the neurodynamical framework, the “Reach Planning” field serves two purposes: 1) initiation of the stochastic optimal controllers that generate actions oriented in specific directions, and 2) integration of diverse information sources related to actions, goals, and situational requirements into a single value representing action desirability or “attractiveness.” The reach planning field receives excitatory input (denoted by green arrows) from the “spatial sensory input” field, which captures the targets’ angular representation in an egocentric reference frame, and the “expected outcome” field which conveys rewards associated with motion in specific directions. It also receives inhibitory feedback (highlighted by red arrows) from the “reach cost” field, which quantifies

the effort needed to move in designated directions, and the “pause” field which operates as a rapid suppressor of planned or ongoing actions during necessary action inhibition. The normalized activity within the reach planning field represents each neuron’s relative desirability against other available options at any particular time and state, with elevated neuronal activity signifying increased desirability to move in its favored direction. Each neuron within the reach planning field connects with a control scheme responsible for generating reaching actions. When a neuron’s activity exceeds a predetermined “action initiation threshold,” the associated controller is activated, generating an optimal policy π_i - i.e., a sequence of motor actions - directed toward that neuron’s preferred direction. The optimal policy π_j is given by minimizing

$$J_j(x_t, \pi_j) = (x_{T_j} - Sp_j)^T Q_{T_j} (x_{T_j} - Sp_j) + \sum_{t=1}^{T_j-1} \pi_j(x_t)^T R \pi_j(x_t), \quad (1)$$

where $\pi_j(x_t)$ is the policy from $t = 1$ to $t = T_j$ to reach towards the preferred direction φ_j ; T_j is the time required to arrive at position $p_j = [r \cos(\varphi_j), r \sin(\varphi_j)]$. r is the distance between the current arm location and the location of the target encoded by the neuron j . x_{T_j} is the state vector at the end of the reaching movement, and matrix S selects the actual position of the arm and the target position at the end of the reaching movement from the state vector. Matrices Q_{T_j} and R define the precision- and the control- dependent cost, respectively (for more details see [29]). The model implements a winner-take-all strategy, where the neuron with the highest activity level wins the competition and determines the reach direction. Once a neuronal group’s activity exceeds the action initiation threshold, a decision is made, and the corresponding reaching movement is executed [29]–[31].

B. Experimental Setup

To evaluate our framework we employed the Kinova Gen3 lite robotic manipulator, fixed-mounted on a tabletop, to perform direct and dynamically-altering reaching scenarios. The robotic arm is set up in a planar configuration, by having the end-effector moving in the horizontal plane and on the same level as its base. The Kinova Gen3 lite is a six-degree-of-freedom robotic manipulator, with a reaching range of 76 cm, and a maximum speed of 25 cm/sec. The selected operating space on the table is $52 \times 47 \text{ cm}^2$ in size and it was used for all our experiments. We used the manufacturer's software (Kinova Kortex) to send motor commands to the onboard controller and actuators. Each actuator has its standalone internal control loop (running at 1 kHz), which also provides its status and sensor feedback (including position and torque) to regulate arm control.

An Astra Pro Plus RGB camera (30 fps live camera feed with 1080p resolution via a USB 2.0 connection) was used for scene understanding and visual-based control. The camera was fixed above the robotic arm to provide a bird's-eye view of the configuration space and detect the desired objects. The arm and camera were connected to a desktop computer, where all information was pulled together for the controller to compute the next robot action. We used plastic balls (7.5 cm diameter) to denote different targets and associated actions. Orange and green balls act as visual beacons for target-reaching and stopping actions, respectively. These were the sole objects placed within the configuration space.

Figure 2 depicts the setup. We developed an application based on the Robot Operating System (ROS) and custom programs in C++ (for robot control) and MATLAB (for NeuCF implementation). The initial end-effector position was set the same across all experiments, and without loss of generality, it was selected as the origin of the world frame. Desired end-effector positions as well as any intermediate positions computed by the controller were also given in the world frame, and trajectory generation ensued to determine the appropriate low-level robot commands (i.e. at the joint level). The latter were computed by directly invoking the robot arm manufacturer's inverse kinematics solver.

C. Scene Understanding

First, an affine transformation was used to compute beacon positions in space based on image plane measurements, i.e.

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = M \cdot \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \iff \begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} a_{00} & a_{01} & b_{00} \\ a_{10} & a_{11} & b_{10} \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}, \quad (2)$$

where M is the transformation matrix of a point (x, y) if the camera frame Π to point (x', y') of the orthographic frame \mathcal{O} . Matrix M can be computed at initialization by using any of the three table corner coordinates in the Π frame. In case the table position changes, the matrix M must be recomputed (i.e. perform extrinsic calibration).

To acquire the beacons' real position in space, we extracted and removed the table background, to exclude false

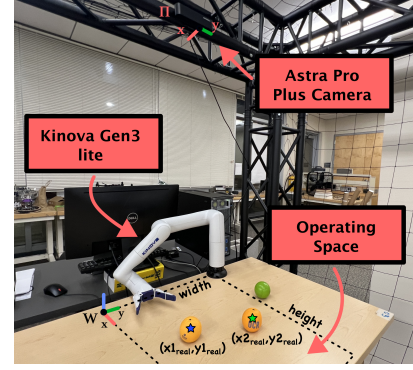


Fig. 2: The robotic arm setup and sensing configuration. A camera provides bird-eye view feedback to the controller. The ball objects on the table are the main target beacons.

positives during localization. An HSV color model transformation was applied on the image plane \mathcal{O} to find the corresponding beacon colors' given their hue value. Binary masking was then applied to obtain the orange and green areas on the image plane. Areas that were less than 15% of the image plane size were excluded from detection. The coordinates of the beacons were then mapped to the real coordinates $(x_{real}, y_{real}) \in \mathcal{W}$ as $x_{real} = (x'/x'_{max}) \cdot width$ and $y_{real} = (y'/y'_{max}) \cdot height$, where variables $width$ and $height$ correspond to the workspace planar boundaries expressed in frame \mathcal{W} (Fig. 2) and (x'_{max}, y'_{max}) are their equivalent representation in frame \mathcal{O} . This way, pixel coordinates $(x', y') \in \mathcal{O}$ of a detected beacon are mapped into \mathcal{W} coordinates, (x_{real}, y_{real}) expressed in cm. The origin was set at the bottom-right corner of the table.

D. Beacon State Description

To describe the status of a beacon we define the 4-tuple $b_t := \{visibility, (x', y'), (x_{real}, y_{real}), t_{vis}\}$. Variable $visibility \in \{\text{"stationary"}, \text{"moving"}, \text{"disappeared"}\}$ indicates the appearance status of the corresponding beacon, while t_{vis} holds the last timestamp that the beacon was detected. All beacon status information is updated in real-time with each received RGB frame. In the case that a beacon disappears we have set a 3 sec delay after t_{vis} to change its status from "stationary" or "moving" to "disappeared." A beacon is considered as "moving" if its position in the x- and y-axis has changed for more than 5% with respect to x'_{max} and y'_{max} , respectively. All this information is transmitted through a custom ROS Topic to the decision and contextual information modules of the NeuCF controller, to provide the current status of the appeared beacons during the reaching scenario. The state of each beacon is important during our experiments since the NeuCF system can adjust the reaching action in real time depending on observed beacon placement.

E. Polynomial Trajectory Generator

A cubic polynomial trajectory generator was used to determine the time scaling function, $s(t)$, of the path given a desired goal on \mathcal{W} frame and a terminal time T . This is computed as $s(t) = a_0 + a_1t + a_2t^2 + a_3t^3$, with $t \in [0, T]$. Instants $s(t = 0)$ and $s(t = T)$ denote the

initial and goal position of the end-effector. The end-effector also needs to start and end at rest, hence $\dot{s}(T) = 0$ and $\dot{s}(0) = 0$. These boundary conditions help set and solve a linear program to compute the coefficients $a_i, i \in [0, 3]$, yielding $a_0 = 0$, $a_1 = 0$, $a_2 = \frac{3}{T^2}$, and $a_3 = -\frac{2}{T^3}$. Since we operate in an open area trajectory generation along the x- and y- axes can be decoupled, and the above process is thus applied twice. Thus, we can obtain the direct path from the cubic polynomial trajectory generator, by providing the total operation time (adjusted to the NeuCF controller) and the desired goal position.

III. EXPERIMENTS, RESULTS, AND DISCUSSION

To evaluate the developed system we conducted five different experiments of reaching scenarios by using one or two target beacons and the stopping beacon. We considered three settings: 1) *static* selection of reaching a stationary existing beacon, 2) the *switch* beacon scenario when the goal target is re-positioned while approaching the target beacon, and 3) the sudden *stop* scenario while reaching for a target beacon. In all cases, we also evaluated the polynomial trajectory generator baseline and compared its output with our system's generated path smoothness and reaching accuracy.

For each experiment, we employed three different beacon setups and repeated each experiment three times. Each setup was tested and repeated the same amount of times for both the NeuCF and polynomial trajectory generation methods. For fairness, the polynomial trajectory generator was set to execute the trajectory at the same operating time as the NeuCF controller. We evaluate our proposed system using path smoothness, reaching goal positional accuracy, generated path length, and higher derivatives of x- and y-axis motion to assess the consistency of acceleration and jerk during motion. We also present the neuronal activation surface plots of the reaching planning field from each case, to demonstrate the activity changes that occurred.

A. Static Beacon Selection

We first evaluated the generation and execution of direct paths toward a selected target (out of possibly two) that remains static throughout the experiment. Table I contains the obtained results. It can be readily verified that the NeuCF-based controller performs on par with the baseline polynomial trajectory generator. Goal-reaching accuracy was high, whereby obtained trajectories have less than 0.87 cm of absolute positioning error in both x- and y-axis, on average. The one-standard deviation of the positioning error of the end effector was less than 0.14 cm in the examined cases. An example is depicted in Fig. 3, showing the NeuCF-based controller can generate a more direct path toward the target.

To evaluate trajectory smoothness, we performed linear regression on the generated x-y trajectory and calculated the coefficient of determination r^2 (whereby a value closer to 1 corresponds to more straight and direct trajectories). NeuCF generates trajectories with $r^2 > 0.99$ (Table I). Attained path lengths are almost equal in length to the ones generated by the direct polynomial trajectory system (over

TABLE I: Experimental Results for *static* Cases

Scenario	<i>static_1</i>		<i>static_2</i>	
Controller	NeuCF	Polynomial	NeuCF	Polynomial
X Error (cm)	0.32±0.02	0.20±0.01	0.20±0.12	0.12±0.04
Y Error (cm)	0.39±0.28	0.74±0.12	0.87±0.14	0.77±0.01
Path Length (cm)	31.02	30.92	28.22	28.83
Straightness r^2	0.9994	1	0.9985	0.9999

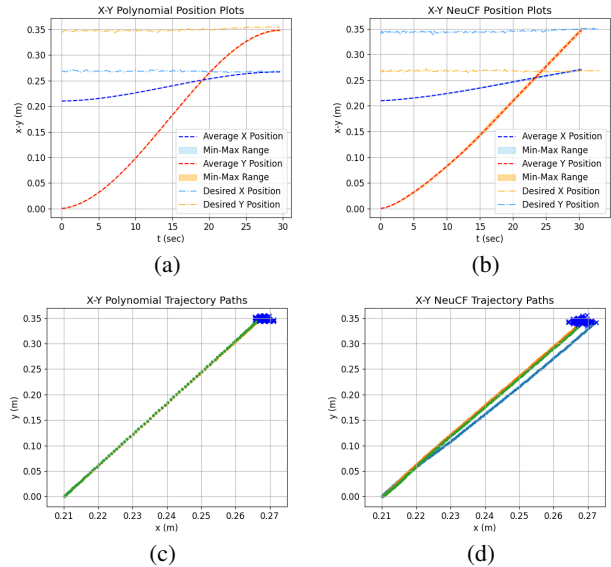


Fig. 3: Resulting trajectories given a selected stationary beacon, close to (27,35) (cm), for the *static_1* scenario. Panels (a) and (b) show the evolution of the x- and y-axis end-effector positions for the Polynomial and NeuCF controllers, respectively. Panels (c) and (d) show the top-down view of the generated trajectories.

TABLE II: Experimental Results for *stop* Cases

Scenario	<i>stop</i>	
Controller	NeuCF	Polynomial
Path Length (cm)	16.15	15.33
Straightness r^2	0.9983	0.9999
Acceleration (cm/sec ²)	0.051±0.25	0.052±0.07
Jerk (cm/sec ³)	0.173±2.55	0.009±0.18

96% match). Figure 4a and 4b show the neuronal activations from initiation of movement toward the selected target. The average total runtime of the experiments was 27.5 sec.

B. Reaching Interruption

We then moved on with testing the ability to interrupt the execution of an ongoing reaching action when a stopping beacon appears in the workspace. This can be applied in either *static* scenarios where the beacons are stationary or during the *switch* scenarios (discussed next) when the robot is trying to reach a new target beacon because of a change in the environment. Obtained results are shown in Table II. The system can afford successful interruption of the reaching action when the stopping beacon appears. Trajectories remain smooth until the end-effector comes to a full stop. The stopping signal does not cause any instability in the last part of the arm's trajectory (Fig. 5). The reported path

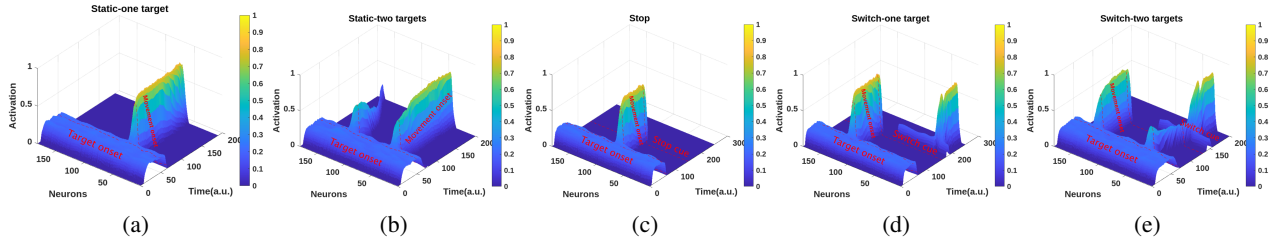


Fig. 4: Activity changes of the 181 neurons of the reach planning field during experiments. Each panel includes the time points when the target appears (target onset), movement initiation (movement onset), and when the stop/switch cue appears (stop cue/switch cue). Note that in case (d), only one beacon is available initially, and then we switch it with a new one, while in (e) both beacons appear initially and one beacon is then removed.

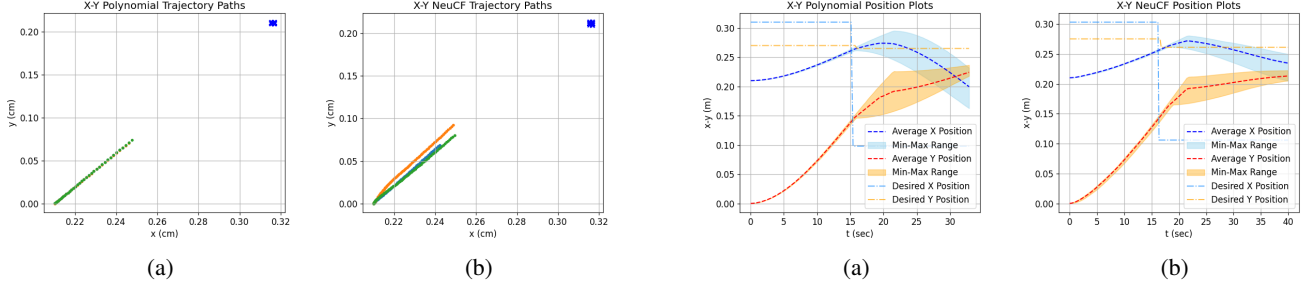


Fig. 5: Generated trajectories by (a) the polynomial and (b) NeuCF controllers during a *stop* experiment. When the green stop beacon appears, both controllers receive an interruption signal and can stop the reaching action successfully.

TABLE III: Experiment Results for *switch* Cases

Scenario	<i>switch_1</i>		<i>switch_2</i>	
Controller	NeuCF	Polynomial	NeuCF	Polynomial
2 nd Der. Variance	5.10e-9	1.59e-8	4.85e-9	3.66e-8
Fractal Dimension	-0.668	-0.744	-0.767	-0.784
Accel. (cm/sec^2)	0.01 ± 0.20	0.02 ± 0.09	0.01 ± 0.22	0.02 ± 0.18
Jerk (cm/sec^3)	0.11 ± 1.62	0.01 ± 0.20	0.15 ± 1.92	0.01 ± 0.39

acceleration and jerk attained relatively low values, although not as smooth compared with the polynomial controller. Acceleration variation was less than 27% compared with the polynomial controller, with the maximum one-standard deviation at 0.07 cm/sec^2 . Variation in jerk in both x- and y-axis was less than 0.30 cm/sec^3 , with the one-standard deviation at 2.6 cm/sec^3 . Figure 4c shows the interrupted neuronal activations after the stopping cue has been received.

C. Switching Beacon Choice

In the *switch* cases we test the dynamic adaptability of our system when the beacons are re-positioned or removed in the middle of executing a reaching action. We consider two cases. In the first case (*switch_1*) one beacon exists in the field which the NeuCF controller selects and generates a path toward it in real-time. During execution, the beacon is removed and a new target beacon is placed at a new position for the robot to reach. In the second case (*switch_2*) two beacons appear initially and the arm starts reaching toward one. Then, we remove the selected target to force the controller to switch its target. During all the experiments in each case, the beacons were removed and replaced at the same time instant and were placed in the same position. We

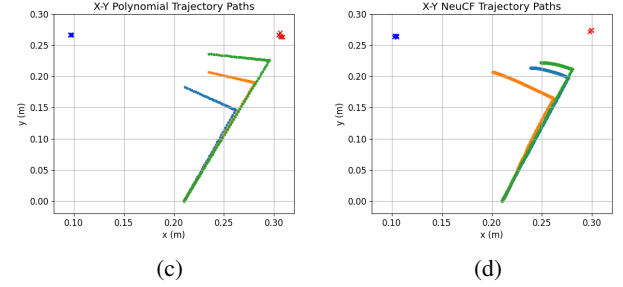


Fig. 6: Experiments during a *switch_2* case. Two target beacons are placed and the target at top-right is selected (in red color). During the reaching action, we remove the target beacon and thus prompt the controllers to re-schedule and approach the other target at top-left (in blue color).

conducted three different beacon placement setups for both *switch_1* and *switch_2* cases. We set a time limit at 36 *secs*.

Since the generated trajectories are more complex due to the on-demand target switch, we employ second derivative and fractal dimension analysis to evaluate the path smoothness. For the former, we numerically compute the second derivative of a trajectory and then measure its variance. In the latter, we analyze the generated plots into a fractal pattern of 50 different box scales and calculate the fractal dimension which reflects the path's spatial complexity.

Results are presented in Table III. There is high linearity in the second derivative analysis providing smooth curves when transitioning to a new target. Scores are overall better compared to the polynomial-based trajectory (smaller positioning variance at $4.98 \cdot 10^{-9}$ compared with the $2.62 \cdot 10^{-8}$ of the cubic polynomial). Fractal analysis also shows the smaller complexity of the NeuCF-generated trajectories by scoring up to 11% smaller fractal score. Figures 6a and 6b depict one of the *switch_2* cases showing both methods output when switching a target while Fig. 6c and 6d show the independent trials during the *switch_2* case and how each controller

steered the system to switch targets. Obtained acceleration in both *switch* cases was similar between the two controllers, while NeuCF demonstrated higher values and variance on path jerk because of the direct re-targeting. Figures 4d and 4e show the neuronal activations for switching NeuCF behavior to reach the available target.

IV. CONCLUSIONS

We demonstrated the potential of the NeuCF controller to perform accurate and dynamic environment-aware target reaching for robotic manipulation. Visual feedback from an off-body camera offers target and robot end-effector position information in real-time which is in turn used by the NeuCF controller to generate smooth reaching trajectories toward a selected target. Several tested cases, including static target reaching, action stopping, and switching to a different target based on changes in the environment at runtime, highlight that the NeuCF controller can afford dynamic real-time re-prioritization for robot reaching. Results showed its robustness in positioning accuracy and smooth trajectory generation, and yielded similar results to a baseline polynomial trajectory generator. Future work will focus on 3D reaching.

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