Research Proposal: Development of a Bio-Inspired Robotic Head-Neck Architecture for Object Tracking and Catching

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1. Introduction

As the manufacturing industry continues to expand, new technologies are needed to further automate production and improve efficiency. As legged robots become more common in high-interaction environments, one of the primary challenges they face is the successful execution of tasks that require tightly coordinated perception, locomotion, and manipulation [1]. Bio-inspired robots present a strong opportunity to address this challenge by developing systems modeled after nature that are adaptable, multifunctional, and capable of autonomous operation in dynamic environments [2].

A robot's ability to interact effectively with its environment is strongly influenced by its end effector and manipulator design. Examining biological mechanisms provides valuable insight into how to balance degrees of freedom (DOF), system complexity, and inertia to achieve smooth and efficient motion. Jaw-inspired mechanisms are particularly effective in applications requiring high gripping forces within compact spaces, where four-bar linkages enable both force and kinematic amplification, especially with short coupler links [3]. Underactuated grippers apply this principle by coupling multiple joints through linkage systems, reducing actuator count while maintaining functional DOF [4]. Effective environmental interaction also depends on joint architecture that replicates the mobility found in biological systems. Many robotic designs achieve this through three intersecting rotational axes, forming spherical joints that enable full spatial orientation through coordinated roll, pitch, and yaw motion using three actuators [5].

A key driver of autonomous systems is robotic hand-eye coordination, which enables robots to analyze dynamic environments and respond in real time. Similar to human reflex testing, tasks such as catching a thrown ball require rapid motion detection and coordinated dynamic response [6]. While inverse kinematics allows the end effector to be oriented within a three-dimensional space through joint angle control, it does not inherently account for the motion of dynamic objects. To address this, a single-camera system can be used for object tracking and trajectory estimation. Techniques such as circle detection can be used to approximate depth, while a Kalman filter enables the system to predict motion and compensate for error in end-effector positioning [6].

Building on these principles, previous FURI research conducted in Spring 2026 focused on the development of a robotic gripper mechanism for object-catching tasks. An underactuated gripper design was selected to reduce inertia and actuator requirements while maintaining a high degree of freedom. Ongoing evaluation will focus on ensuring the gripper can respond quickly enough to interact with the ball at the intended contact point.

Extending on this prior work, this research proposes a robotic system with a three degree-of-freedom spherical joint combined with an underactuated gripper for reliable grasping and catching tasks. A single-camera object detection system will be used to perform trajectory analysis and support dynamic catching motions. This design enables more responsive and adaptive behavior in environments requiring high levels of human-robot interaction and rapid response, while also providing a framework for applying bio-inspired principles to the automation of complex tasks.

2. Activities and specific goals

In this research, we aim to address the following questions: (1) How can a bio-inspired head-neck architecture be modeled and implemented as a robotic system? (2) What dynamic and control requirements are necessary to enable reliable catching motions? (3) How can robust hand-eye coordination be achieved for real-time object interception? To answer these questions, I have identified 5 key milestones. As part of the Sun Robotics Research Lab, I will also have access to support from other students, which will help improve my efficiency on these tasks.

Task 1: The first task involves refining the existing underactuated robotic gripper developed in Spring 2026 to improve responsiveness and reduce inertial effects. Ensuring that the gripper can move quickly and smoothly to intercept the ball and grasp it securely is critical to the project's success.

Task 2: The second task focuses on designing a spherical joint to provide the system with a three DOF range of motion and integrating it with the gripper assembly. This will allow the gripper to orient itself appropriately to handle balls approaching from different trajectories. Special attention will be given to positioning the actuators near the base to minimize inertia and support smooth movement. Design iterations will be conducted as needed to refine and optimize overall performance.

Task 3: The third task focuses on developing the controller by implementing an inverse kinematics model. This will enable the end effector to be oriented within a three-dimensional space through joint angle control. Testing will be conducted to verify that the system achieves the desired orientations specified by the model.

Task 4: The fourth task involves implementing a vision system to enable the robot to detect the ball's motion and adjust the gripper accordingly. A single-camera motion tracking device will be mounted to the end effector to capture the ball's position within the environment. To address the limitations of a single camera, a circle detection algorithm will be used to estimate depth based on changes in the observed radius. Additionally, a Kalman filter will be implemented to predict motion and compensate for error in end-effector positioning based on previous observations.

Task 5: The final task involves testing the fully assembled system to evaluate its dynamic behavior. The focus will be on how effectively the robot can respond and adjust its motions in real time. A variety of ball trajectories, including throwing, rolling, dropping, and bouncing, will be tested to assess the system's adaptability. Qualitative observations of successful and unsuccessful catches will be used to evaluate hand-eye coordination and identify areas for further refinement.

3. Aligning with Fulton School's research themes

This research contributes to ASU and society, with applications across academic and industrial settings. Specifically, the research aligns with the **Fulton research theme** of **producing competitive manufacturing in an advanced economy.** Robots have long transformed manufacturing and supply chains by reducing human involvement and improving efficiency. Bio-inspired robotics offer the potential to develop systems that replicate natural movement, responsiveness, and adaptability, making them well suited for environments that demand high levels of coordination and precision [1]. When adapted for legged robotic platforms, these systems can closely emulate human and animal motion, providing hand-eye coordination that is critical for performing complex manufacturing tasks autonomously.

Works Cited

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