AgiLimb: Embodied Agile Robotic Arm by Integrating Digital Reflex and Seamless Action Takeover

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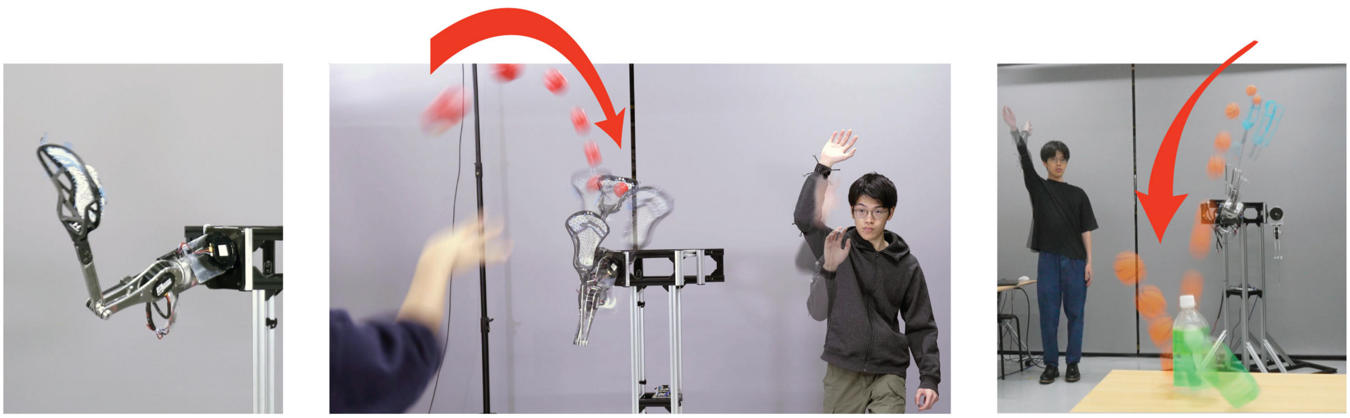

Figure 1: Catch and throw with human-operated agile robotic arm.

ABSTRACT

Performing sports skills with a human-operated robot is a challenging task. The key to human-robot-human (HRH) interaction is to combine the physical capabilities of a robot with the flexibility of a human. We developed the AgiLimb system to enable operators to transcend their own perceptual and physical abilities in a robotic experience while maintaining a sense of agency. The system introduced fast vision-based digital reflex to overcome the delay in human higher-order visual feedback. In addition, the system incorporates action takeover mechanism to improve the accuracy of the motion. The basis for agile motion is a quasi-direct-drive robot manipulator designed specifically for this application. In the demonstration, visitors will experience operating the AgiLimb system that moves and reacts like their own body.

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CCS CONCEPTS

• **Computer systems organization** → **Robotics**; • **Human-centered computing** → *Interaction design*; • **Hardware** → Emerging technologies.

KEYWORDS

Sense of agency, Human-machine integration, Teleoperation, Human-robot Interaction (HRI)

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1 INTRODUCTION

Real-time robot control and sensing of human movements enable a robotic body to serve as an avatar that transcends human precision and speed. However, designing anthropomorphic robots that allow the operator to maintain a sense of agency remains a problem.

Robots can surpass human physical capabilities. For example, combining robot manipulators with high-speed vision has enabled tasks like intercepting a bounced ball [Monforte et al. 2023] and

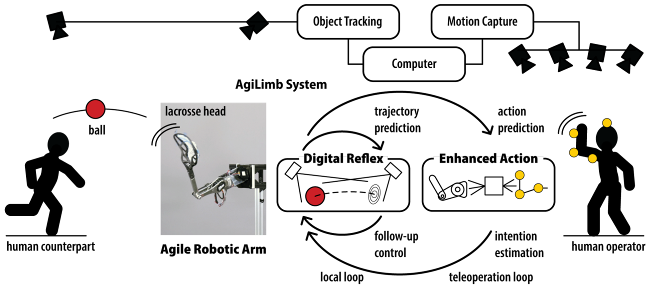

Figure 2: AgiLimb system overview.

performing baseball movements [Senoo and Ishii 2021]. These studies focus on enhancing robot performance in specific tasks, unlike human-operated robots, which rely on operators for decision-making, planning, and diverse motions.

Motion assistance by autonomous systems enhances human-operated robots. For example, a shared control approach has been effective for object transportation tasks [Selvaggio et al. 2022]. Other studies include semi-autonomous impedance regulation [Muratore et al. 2018]. These studies suggest that movement enhancement at the meta-level is necessary, beyond merely following human trajectories.

A few studies have explored robot-mediated interactions that improve task performance while maintaining a sense of agency. For example, Parallel Ping-Pong achieved parallel embodiment by automatically switching information on a head-mounted display for a user playing against two opponents [Takada et al. 2022].

We introduce the AgiLimb system that combines a fast digital reflex loop with enhanced robotic movements that interpret human intent, accommodating teleoperation delays. The system features a specially developed agile robotic arm capable of acceleration and deceleration beyond human ability. The system can catch a ball using digital reflex and throw a ball using enhanced actions.

2 AGILIMB SYSTEM

Figure 2 shows the overview of AgiLimb system, which integrates vision-based digital reflex and seamless action takeover improving robotic limb precision based on human intent.

2.1 Agile Robotic Arm and Motion Capture

The agile robotic arm (forearm: 284mm, upper arm: 337mm) composed of four quasi-direct-drive motors (AK80 series, T-motor). Angle commands are sent to the motors from a PC through a microcontroller at a 100 Hz cycle. The robotic arm is remotely operated to follow the rotation of the motion-captured user's arm.

2.2 Vision-based Digital Reflex for Catching

Since the delay between human visual stimuli and the onset of motion is approximately 250 milliseconds, it is not possible to take advantage of the physical capabilities of agile robotic arms by following human motion. Therefore, our digital reflection uses high-speed vision-based ball trajectory prediction to predict the arrival point in real time, enabling automatic control to catch the ball. The ball trajectory prediction system uses two cameras at up to 140 FPS to color track the red ball, triangulate it to capture its position, and use a kinematic model to predict the ball's trajectory. The processing time from color tracking to the start of robot arm motion is about 60 ms, which is faster than the human visual reflex rate.

2.3 Enhanced Action for Throwing

This robotic arm, designed for agility, is difficult to operate as intended by the user because its structure is different from human joints. Therefore, this system detects the throwing intention from the user's arm motion, and estimates the throwing direction and velocity from the 300ms motion prediction based on the Minimum Jerk Model. From these, a throwing motion suitable for the robotic arm to achieve the user's intention is generated.

2.4 Seamless Action Takeover

The robot joint angle commands are a blend of manual and automatic control according to $q_{\text{blend}} = (1 - \alpha) \cdot q_{\text{manual}} + \alpha \cdot q_{\text{auto}}$. Here, q_{manual} represents the joint angle of the manual control, q_{auto} represents the joint angle of the generated motion, q_{blend} is the blended joint angle, and $\alpha \in [0, 1]$ is the blending ratio. The value of α is set to 0, meaning the robot is under manual control. When a catch or throw flag is detected, α increases immediately, intervening assistive control. While setting α to 1 results in complete automatic control, it is also possible to choose a lower value to allow for fine user adjustments. After the motion is completed, α gradually decreases to 0, smoothly returning manual control.

3 CONCLUSION

We built the AgiLimb system to control an agile robotic arm while preserving the user's sense of agency. The system integrates digital reflex and seamless action takeover to enhance catching and throwing.

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