Towards an Embodied Biohybrid Robotic Platform for Interaction with Honeybees

Hang Wang
Biohybrid Robotics Lab
Department of Computer Science
Durham University, UK
hang.wang@durham.ac.uk

Mohsen Zahmatkesh
Swarm & Computational Intelligence Lab
Department of Computer Science
Durham University, UK
mohsen.zahmatkesh@durham.ac.uk

Martin Stefanec
Department of Zoology
Institute of Biology
University of Graz, Austria
martin.stefanec@uni-graz.at

Ali Emre Turgut
Mechanical Engineering Department
Middle East Technical University
06800 Ankara, Turkey
aturgut@metu.edu.tr

Jiří Ulrich, Tomáš Krajník
Artificial Intelligence Centre
Faculty of Electrical Engineering
Czech Technical University, Czechia
{jiri.ulrich,tomas.krajnik}@fel.cvut.cz

Farshad Arvin
Biohybrid Robotics Lab
Department of Computer Science
Durham University, UK
farshad.arvin@durham.ac.uk

***Abstract*— Robotic interaction with insects in a controlled yet unobtrusive manner is essential for advancing research in biology and biohybrid systems. Micro-robots offer a unique opportunity for such interaction due to their small size, adaptability, and potential for integration into complex biological environments. In this paper, we present a biohybrid robotic platform designed to detect and follow the position of a queen bee projected onto a screen using real video recordings from our observation hives. The robot can identify the location of queen and execute movement strategies to maintain specific spatial configurations with her, emulating behaviours of the queen's retinue bees. This queen-following capability establishes a controlled experimental framework for studying future insect–robot interactions and sets the stage for embodied robotic agents that may eventually operate inside honeybee colonies.**

***Index Terms*—Biohybrid Robotics, Insect-Robot Interactions, Honeybees.**

I. Introduction

The western honeybee (*Apis mellifera*) represents one of the most advanced forms of social organisation on our planet [1], surpassing in many ways the social organisation of humans. Within such eusocial systems, individuals exist in complete interdependence, forming what many consider a "superorganism" [2]. Honeybee colonies comprise tens of thousands of individuals confined to a relatively small space, with each member performing specific functions critical to collective survival [3]. Unlike other eusocial insects that nest underground, such as ants, honeybees can inhabit structured, observable hives, making them particularly suitable subjects for studying complex social structures [4]. The colony revolves around a reproductive queen, while worker bees maintain colony homeostasis through tasks including temperature regulation for brood development, nutrient collection, and environmental maintenance [5]. Despite their accessibility, conventional human observation methods remain limited in capturing the complex dynamics of the hive activity. A human observer cannot simultaneously monitor multiple interactions, maintain continuous observation without fatigue, or avoid introducing observational biases [6]. Furthermore, traditional experimental approaches often involve procedures that significantly disturb the colony. These limitations could be resolved through technological solutions that can both observe hive activities through computer vision and interact with colonies in minimally invasive ways.

Researchers continually try to design and develop biohybrid robotic systems emulating the behaviour of biological systems. The main goal is to achieve reliable robotic control for specific tasks in challenging environments, such as interacting with bees inside a honeybee hive. Due to continuous breakthroughs in microfabrication and high-precision manufacturing, many researchers have developed various micro biohybrid robotic systems. For example, Chukewad et al. [7] proposed an insect-sized flapping robot (RoboFly) capable of flight, as well as traversing terrestrial and aquatic surfaces. Yang et al. [8] proposed a cyborg system based on the Madagascar hissing cockroach (*Gromphadorhina portentosa*) that uses swarm-based control to navigate complex environments. These biohybrid robots, inspired by the physical and behavioural characteristics of different insects, are designed to perform specialized functions such as search and rescue. Goldsmith et al. [9] introduced the Drosophibot II robot to study the motion model of fruit fly leg postures; however, they did not investigate the interactions of the robot in nature, which is a key goal of biohybrid robotics. Barmak et al. [10] proposed a biocompatible robotic system that explores the collective thermoregulation behaviour of bee colonies through thermal sensors and actuator arrays. Michelsen et al. [11] investigated the informational encoding of the bee waggle dance using robotic bees, while Romano et al. [12] employed a biomimetic locust demonstration robot to investigate the stress responses of swarming locusts in specific environments.

These studies not only focused on the efficacy of insect swarm behavioural mechanisms but also tried to develop robotic systems that demonstrate the underlying strategies of swarm systems, thereby enabling biohybrid systems to collaborate with biological counterparts [13]. Nevertheless, they still lack long-term interaction with real animals and simply replicate the unique behaviours of individual organisms without fully exploring their collective impact. At present, the interaction between biohybrid robots and biological groups is often constrained by the complexity of natural environments and the challenges associated with high-precision manufacturing technologies. Therefore, developing a robotic platform that facilitates prolonged observation and interaction with insect groups, and integrating it with biohybrid robotic systems, represents an effective solution. Papastyros et al. [14] proposed a robotic platform, called BOBI, to observe and interact with microorganisms, and investigated the interaction behaviour of the rummy-nose tetra (*Hemigrammus rhodostomus*) by incorporating a wheeled robot (LureBot). In other studies, Rekabi-Bana et al. [15]–[17] designed and developed a robotic system aimed at interacting with honeybees within the hive. In their follow-up study, they developed an autonomous robotic observation and behavioural analysis (AROBA) system [18], which is also used in this paper as our base platform.

In this paper, we present an autonomous biohybrid robotic system that responds to video projections of a queen bee displayed on a screen. Unlike traditional in-hive tracking, which is often limited by visual occlusion, uncontrolled environmental variables, and difficulty in repeatability, our setup enables precise and repeatable experiments under controlled conditions. The queen's behaviour is replayed, and the robot executes spatial movements to maintain a defined position relative to her image. The robot operates in the vertical plane, adjusting its posture in response to the projected location of the queen. This helps us, as robotic engineers, to focus primarily on improving our mechatronic systems and control algorithms without becoming involved in the complexity of real honeybee colonies and the associated risk. This controlled interaction model serves as a foundation for future embodied systems capable of participating in real-time dynamics within live honeybee colonies.

II. Biohybrid Robotic System

A. Mechatronics Design

Figure 1 illustrates our robotic experimental setup that was used in this study.

1) AROBA System: AROBA System [18] is a multifunctional platform developed within the EU RoboRoyale project[1]. As shown in Fig. 1, the AROBA system can accurately locate the spatial position of individual bees inside the hive. Its aluminium profile frame structure not only ensures high stability, but also provides substantial structural strength, making long-term observation of honeybee behaviour possible with minimal disturbances. The multifunctional platform, which can be used to mount complex interactive devices, is fixed

[1]https://roboroyale.eu/

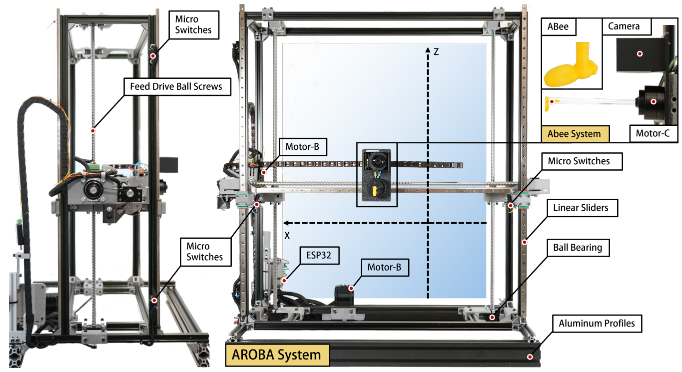

Fig. 1. Hardware architecture of the autonomous biohybrid robotic system used in this paper to follow the queen and move our artificial bee (*ABee*).

to a vertical plane ball screws and linear slide guides. Two high-precision closed-loop stepper motors enable movement along the horizontal axis (X) and the vertical axis (Z). The two-dimensional motion of the platform is controlled in a closed-loop manner by an ESP32 development board installed on the rear left side of the system. The integrated control system within the ESP32 board converts the acquired position data into control commands for the actuators, simultaneously obtaining real-time feedback from each actuator. In [18], the AROBA system was deployed in observation-only configuration and its multifunctional platform was equipped only with a camera. In the work presented hereby, the AROBA platform is equipped with a robot that can physically interact with the bees.

2) Artificial Agent (ABee): ABee (shown in the top right of Fig.1) is a biohybrid robotic prototype designed to interact with bees inside a beehive. Its appearance mimics the body of a bee and is entirely fabricated using 3D printing with bio-integrative materials. The hollow design within its torso is intended to house miniature sensing devices in the future. ABee can rapidly rotate to any angle using its servo motor that is attached to the AROBA system (see the central part of Fig.1). In addition, the servo motor provides real-time feedback of the angular position of ABee to the central control system. The main goal here is to keep ABee always facing the queen.A high-definition camera module (Harrier 10x AF Zoom USB/HDMI Camera) is installed directly above the ABee platform to recognise the position and rotation angle of the queen bee in the hive, which is the initial data source for controlling the ABee to gradually approach the queen bee.

B. Software System

This section describes our control mechanism for hardware components and the movement of ABee. The control center includes software control (PC) and an AROBA Motion control (shown in Fig. 2).

The Software Control unit will be used to process acquired data and converts it into control commands for the AROBA system, which will be input into the AROBA Motion Control. Firstly, the camera module will input the wide-angle images

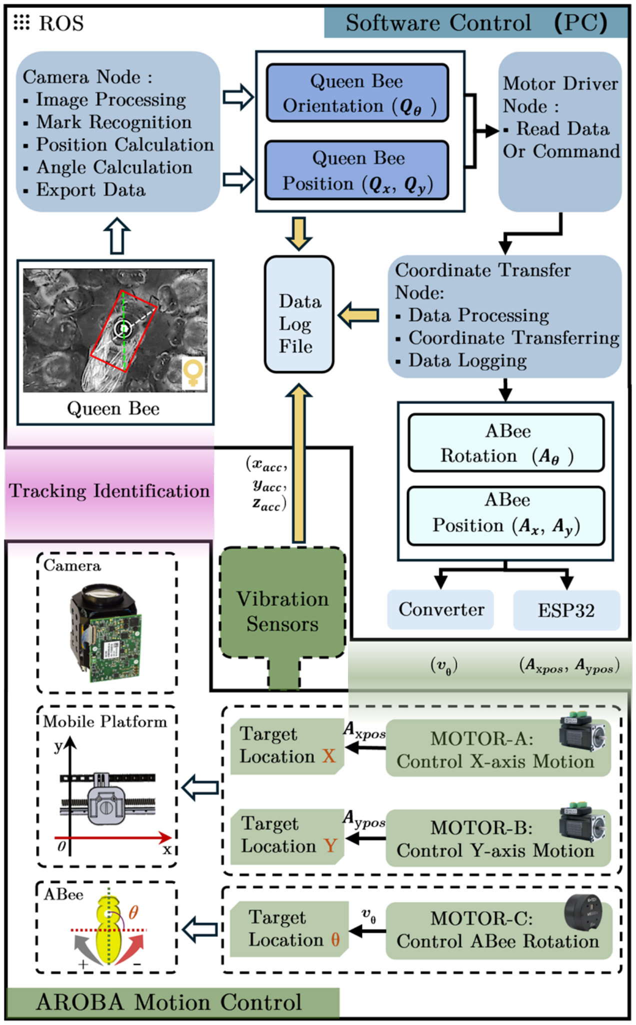

Fig. 2. Design framework diagram of controller. The controller includes the *Software Control (PC)* and the *AROBA Motion Control*.

of the hive into Camera Node. Camera Node will process the input images by identifying the markers on the back of the queen bee to determine its relative position (Q_x, Q_y) and orientation angle (Q_θ). These data will be saved as the position information of the queen bee and read by Motor Driver Node. This node will send the data or commands (BeeGo) to Coordinate Transfer Node, which will further process them by converting the coordinate system to ABee's relative position (A_x, A_y) and orientation angle (A_θ) data, and convert it into target position $(A_{xpos}, A_{ypos})$and speed data (v_θ) via the ESP32 board and USB-to-RS485 for secondary conversion, and input them into the AROBA Motion Control. All data will be recorded and stored in log files.

We developed a motion control library, called *BeeGo*, which can implement low-, middle- and high-level commands, such as `StopAgent()`, `Goto(`x, y`)`, or `FaceQueen(`ϕ`)` respectively. Ultimately, the library should be able to implement complex behaviours such as `WaggleDance(`l, ψ, f`)`, which is a high-level, complex social behaviour and requires more biological study. In this paper, we focus on the `FaceQueen(`ϕ`)` behaviour which is crucial to emulate the behaviour of the bees that clear and groom the queen. Hence, we developed a formation control algorithm that will be described in the next section.

TABLE I
EXAMPLE OF BEEGO CONTROL COMMANDS

	Command	Descriotion
LL	`MoveAgent` (v, ω)	Move ABee with linear and angular velocities of v and ω
	`StopAgent()`	Stop agent and reset velocities
	`TurnAgent(`θ, ω`)`	Rotates ABee θ degree with ω velocity
ML	`GoXY(`x, y`)`	Transfers ABee to position x and y
HL	`FollowQueen()`	ABee follows queen trajectory
	`FaceQueen(`α`)`	Position ABee face to queen with α degree orientation
	`WaggleDance(`l, ψ, f`)`	ABee performs a dance with length of l, angle of ψ and frequency f

LL: Low-Level, ML: Mid-Level and HL: High-Level commands.

C. AROBA Motion Control

The Motion Control unit will control the position and orientation of the ABee, and the camera module mounted above the ABee move together to track and identify the queen bee. Firstly, the ESP32 board transmits accurate target position (A_{xpos}, A_{ypos}) and velocity (v_θ) to the motors in the AROBA system. Among them, Motor-A and Motor-B will control the ABee to move to the target position, and Motor-C controls the ABee to rotate to the specified angle position at the speed of (v_θ) to achieve the goal of `FaceQueen`. The camera module continuously tracks and identifies the position and orientation of the queen bee to ensure real-time updates of the ABee position.

The control system for Motor-C (ABee motor) is discussed in detail in the following Section.

III. DYNAMIC IDENTIFICATION AND ROBUST CONTROL

A dynamic identification system and robust control for the ABee motor are developed in this section to focus on the `FaceQueen(`ϕ`)` task in this robotics system. In this case, robust control algorithms have been developed for such high-sensitivity conditions [19].

A. Identification Theory

The ABee motor dynamics are modeled as a linear time-invariant (LTI) system:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) + Du(t) + v(t) \end{cases}, \quad v(t) \sim \mathcal{N}(0, \sigma^2) \quad (1)$$

with state $x(t) \in \mathbb{R}^n$, velocity input $u(t)$, angular position output $y(t)$, and measurement noise $v(t)$.

Lemma 1. *The step input satisfies* $\exists T, \alpha > 0$*:*

$$\frac{1}{T}\int_t^{t+T} u(\tau)u^\top(\tau)d\tau \succeq \alpha I, \quad \forall t \geq 0 \quad (2)$$

guaranteeing unique identifiability of (A, B, C, D).

The identification procedure comprises:

Algorithm 1 Subspace Identification (N4SID)

1: Construct iddata $\mathcal{I} = (y_{1:N}, u_{1:N}, T_s)$ from experimental data

2: Solve prediction-error minimisation:

$$\min_{\theta} \sum_{k=1}^{N} \|y_k - (C(qI - A)^{-1}B + D)u_k\|^2 \tag{3}$$

3: Transform to observable canonical form via T:

$$A = \begin{bmatrix} -a_1 & 1 \\ -a_2 & 0 \end{bmatrix}, \; B = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}, \; C = \begin{bmatrix} 1 & 0 \end{bmatrix} \tag{4}$$

4: Discretize with zero-order hold equivalence:

$$x_{k+1} = e^{AT_s} x_k + \left(\int_0^{T_s} e^{A\tau} d\tau \right) B u_k \tag{5}$$

Model fidelity is quantified via normalised RMS error:

$$\text{NRMSE} = 100\% \times \left(1 - \frac{\|y - \hat{y}\|_2}{\|y - \bar{y}\|_2}\right), \quad \bar{y} = \mathbb{E}[y] \tag{6}$$

The identified second-order model satisfies the spectral consistency criterion:

$$\|G - \hat{G}\|_{\mathcal{H}_\infty} < 0.15 \quad \text{over } \omega \in [0, \pi/T_s] \tag{7}$$

ensuring reliability for control synthesis.

B. Robust Control Design for the ABee

Define tracking error $e(t) = x_{2,\text{ref}}(t) - x_2(t)$ and integral error $z(t) = \int_0^t e(\tau) d\tau$.

Theorem 1. *For gains $K_p, K_i, K_d > 0$ satisfying*

$$K_p > \frac{D}{\epsilon}, \quad \epsilon > 0, \tag{8}$$

the control law

$$u_{PID} = K_p e + K_i z - K_d \dot{e} \tag{9}$$

ensures ultimate boundedness:

$$\limsup_{t \to \infty} |e(t)| \le \frac{D}{K_p}. \tag{10}$$

Proof. Consider Lyapunov candidate $V = \frac{1}{2}e^2 + \frac{1}{2K_i}z^2$. Taking derivative:

$$\dot{V} = e\dot{e} + \frac{1}{K_i} z e$$

Using the system $\ddot{x}_2 = -ax_2 + u + d(t)$ and the control law gives:

$$\dot{V} \le -K_p e^2 - K_d \dot{e}^2 + |e| D$$

Applying Young's inequality completes the proof. □

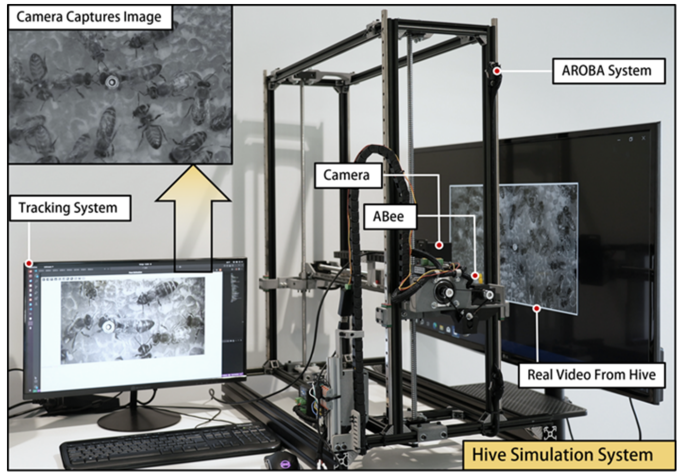

Fig. 3. Hive Simulation System.

Sliding Mode Control (SMC)

Define sliding surface $s = \lambda e + \dot{e}$ with $\lambda > 0$.

Theorem 2. *For $\eta \ge D + \delta$ ($\delta > 0$), the control law*

$$u_{SMC} = -\lambda \dot{e} - \eta \cdot \text{sat}(s/\epsilon) \tag{11}$$

guarantees reaching condition $s\dot{s} \le -\delta|s|$, achieving $s(t) = 0$ in finite time $t_r \le |s(0)|/\delta$.

Proof. Let $V = \frac{1}{2}s^2$. Then:

$$\dot{V} = s(\lambda \dot{e} + \ddot{e}) = s(-\eta \cdot \text{sat}(s/\epsilon) + d(t)) \le -\delta|s|$$

By comparison lemma, $|s(t)| \le |s(0)| - \delta t$. Sliding phase dynamics $\dot{e} = -\lambda e$ yield exponential convergence. □

Lemma 2. *The smoothed saturation function*

$$\text{sat}(s/\epsilon) = \tanh(s/\epsilon) \cdot \min(1, |s/\epsilon|) \tag{12}$$

satisfies $\lim_{\epsilon \to 0} \text{sat}(s/\epsilon) = \text{sgn}(s)$ while maintaining $|u_{SMC}| \le \eta$.

IV. Experimental Setup

A. Hive Simulation System

To implement precise tracking and interaction of the queen bee within the hive using the AROBA system, a high-definition 43” LCD screen was used to simulate the real scene of the hive. The AROBA system was faced to the screen, and the image processing modules track the queen bee in the screen and determine the position and orientation of the queen bee.

The proposed system will calculate the target position and rotation angle of ABee by analysing the data obtained from the tracking module, and control the AROBA system and ABee movement. The entire process will be in a closed-loop control state, and the display screen located on the left side of the AROBA system will show real-time footage captured by the camera. Figure 3 shows the layout of the AROBA system, high-definition display screen, camera, and ABee, as well as the real-time image display of the camera.

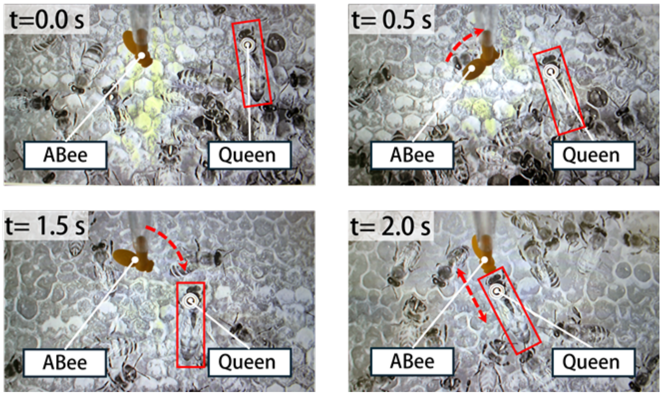

Fig. 4. A sample run of the `FaceQueen` command rotating Abee.

B. Queen Tracking

To allow reliable and real-time tracking, we marked the honey bee queen with the WhyCode [20] fiducial marker. It is a vision-based localisation system providing the full 6 DOF pose estimation and unique identification. The marker is black-and-white, and with its circular shape, it resembles the commonly used markers by the beekeepers in standard hives. The marker was scaled to 2.162 mm in diameter, so it would not obstruct the queen's movement as it was attached to her thorax. We placed four additional markers in the hive corners to establish the hive coordinate system and to provide reference points for the AROBA robot to calibrate its odometry and reduce drift over long-term operation. The AROBA system is set to keep the queen in the image centre, so when she moves, the camera follows her. The movement is based on proportional control with respect to the image centre.

In this paper, we used the position and orientation of the queen from previously conducted experiments in a real honeybee colony.

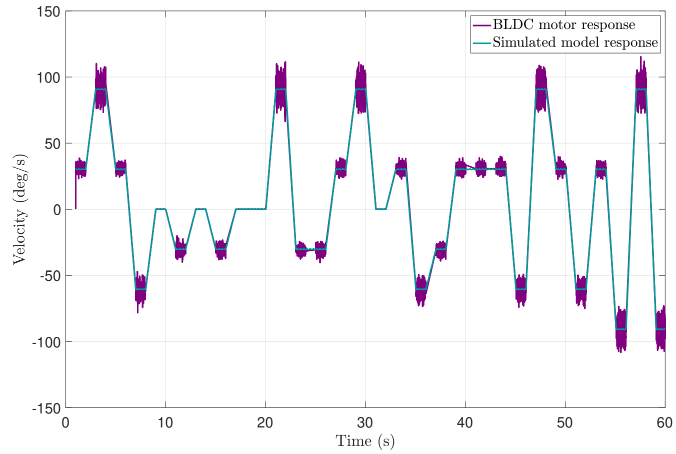

Fig. 5. Validation results showing measured vs simulated velocity (NRMSE = 90.58%).

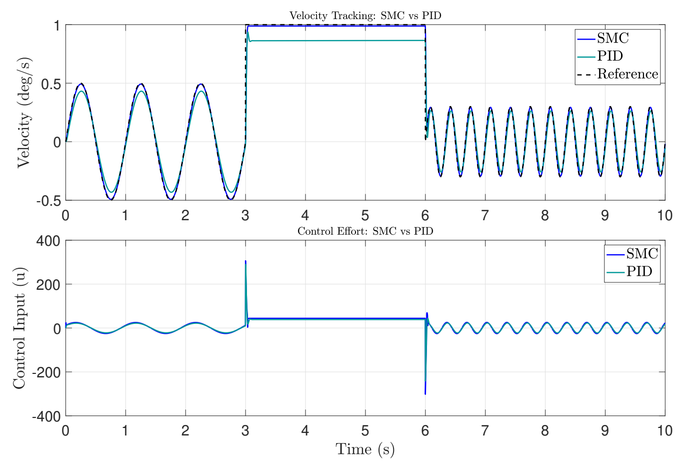

Fig. 6. SMC vs. PID: Velocity tracking and control input comparison.

V. Results

In this section, an autonomous passive interaction (shown in Fig. 4) with the queen is presented. The simulation and experimental results of actuation system identification and two different control methods are presented in this section. As shown in Fig. 5, the dynamic model of the ABee angular actuator is identified using different velocity step commands. This dynamic model will be utilised in future works for disturbance and uncertainty rejection purposes. As a result of highly accurate controllers, smoother interaction will be granted [21], [22]. Based on the discussion in the controller design section, the response and control effort of the modelled system are presented in Fig. 6.

Accordingly, although both controllers generated almost analogous commands, the SMC surpassed the PID controller in velocity tracking performance.

Figure 7 presents the tracking performance of both SMC and PID controllers. It is worthwhile to mention that the rise time and the final reaching time of the PID controller are less than those of the SMC (as shown in Fig. 8), thanks to its simplicity. However, in the case of tracking error, it appears that it lacks some adaptability during abrupt queen angle changes. In addition, the control effort of the SMC has exceeded in optimality and real-world applications.

According to the obtained results, the SMC, as a robust controller, was a better approach for adapting to the queen's abrupt movements, which are considered uncertainties and disturbances. Also, it requires less control effort, resulting in reduced system friction and more optimal energy consumption. Furthermore, it is an inspiring approach for developing more disturbance-resilient controllers for smoother interaction in future works.

VI. Conclusion

This study demonstrates the feasibility of a biohybrid robotic system capable of responding to the movements of a queen bee projected on a screen using real colony footage. By maintaining spatial alignment with the queen's position in the video, the robot emulates key aspects of natural positioning behaviour in a fully controlled and repeatable environment.

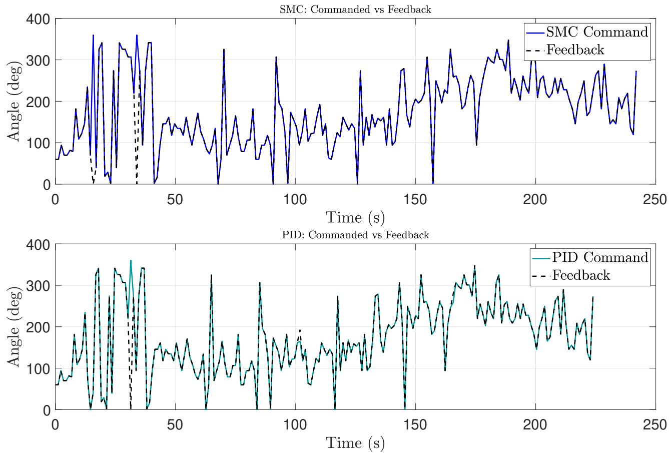

Fig. 7. Real Experiment position tracking error and control effort comparison.

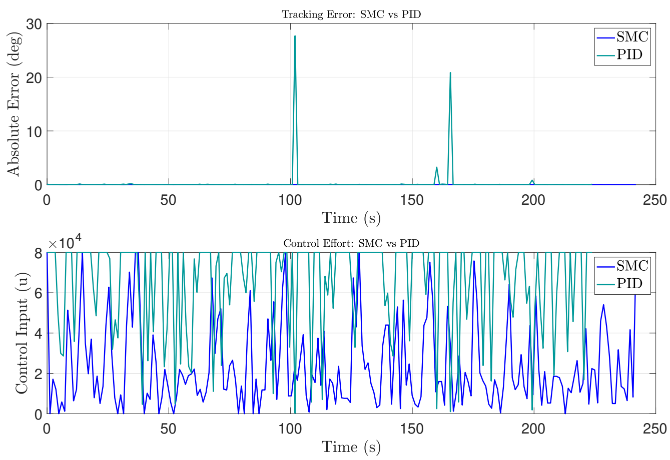

Fig. 8. SMC vs. PID: Position tracking error and control effort comparison.

This screen-based setup offers a flexible alternative to traditional in-hive experiments, overcoming challenges such as occlusion, variability, and limited experimental control. The system establishes a foundational framework for exploring future insect–robot interaction strategies, ultimately enabling the development of embodied agents capable of meaningful engagement within live colonies.

Acknowledgement

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