Mechatronic Design for Multi Robots-Insect Swarms Interactions

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***Abstract*— This paper presents the concept of a robotic system collaborating with a swarm of social insects inside their hive. This robot consists of a micro- and macro-manipulator and a tracking system. The micro-manipulator uses bio-mimetic agents to interact with an individual specimen. The macro-manipulator positions and keeps the micro-manipulator's base around the given individual while moving in the hive. This individual is tracked by a fiducial marker-based visual detection and localisation system, which also provides positions of the bio-mimetic agents. The base of the system was experimentally verified in a honeybee observation hive, where it flawlessly tracked the honeybee queen for several hours, gathering sufficient data to extract the behaviours of honeybee workers in the queen's vicinity. These data were then used in simulation to verify if the micro-manipulator's bio-mimetic agents could mimic some of the honeybee workers' behaviours.**

I. Introduction

The design and development of robotic systems capable of interacting with animals is a relatively new research field that persuades many researchers to face the complexities and find new solutions for robotic and biological research works. Robot-animal interaction allows researchers to observe and investigate animal behaviours differently. Furthermore, it helps to inspire from living species to design various algorithms and structures for robotic systems [1]. This new area needs multidisciplinary perspectives toward the problem regarding the objectives that might be more robotics or biological [2] [3].

Robot-insect interaction would be the most challenging subdomain of the robot-animal interaction [4]. Nevertheless, this field is persuasive because of its significant contributions to micro-robotic research work. The leading robotic objectives of robot-insect investigation can be classified into three main categories: i-the individual behavioural study that leads to inspiring new control methods and structural design, ii-the social behaviour investigations that allows determining novel communication strategies and multi-agent interaction disciplines, iii-influencing, where actuation will enable robotic systems to affect or control the insects behaviours [2], [5].

This work was supported by EU H2020-FET-OPEN RoboRoyale project [grant number 964492].

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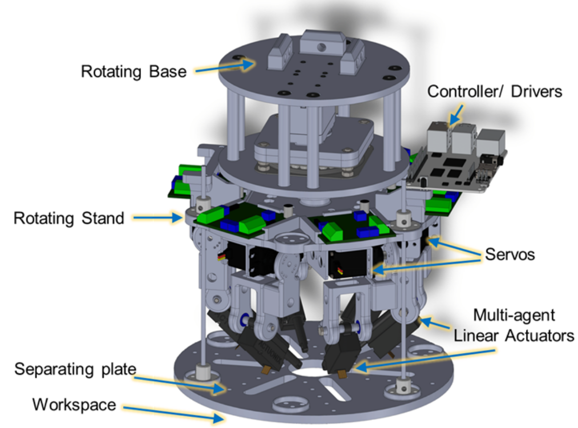

Fig. 1. A multi-agent micro-mechatronic mechanism that was designed for interacting with the social insects to affect their behaviour, and subsequently, the activity of the entire social insect swarm.

For example, Möller [6] presented a novel vision-based navigation inspired by the insect visual homing method, which is a sample of the robot-insect investigation. Furthermore, cybernetic systems can benefit from the social species study results. For instance, [7] presents a novel decentralised situated control for a networked system. In other studies, researchers attempted to investigate robot-species interaction to investigate the behaviour of insects such as Crickets and determine how they can influence their behaviour with various strategies [8]–[10]. In a different approach, [11] shows a new approach to investigating the adaptability features of insects using miniature robots. Moreover, some studies evaluate different intelligent algorithms to learn from insects and influence their behaviour simultaneously [3], [12], [13]. Although these studies concentrate on individual behaviour, other investigations attempt to determine the social treatments, particularly the communication strategies between the colony members via chemical substances such as pheromone transfer [14], [15] or particular body movements like waggle dance in honeybees [16]. Nevertheless, inspiration from insects is not restricted to intelligent algorithms for behavioural control. Such studies allow researchers to design and build new mechanical structures and actuation systems for micro-robots working in different workspaces [17], [18].

These robot-insect research works establish the importance of different aspects of both robotics and biological problems. One of the most intelligent and challenging social species for such studies is honeybees. However, only a few research teams tried to conduct robot-insect experiments with these species due to the intricate issues toward the bio-compatibility that makes the robots acceptable among the colony [19]. Although researchers established significant results for robot-worker bees interactions by the development of a bio-mimetic system to communicate with worker bees through waggle dance [16], [20], the interaction with the queen honeybee will be more complicated due to the colony's sensitivity to its vital role in the hive. Meanwhile, they can influence the whole colony performance [19]. Accordingly, it is necessary to utilise different approaches to design a delicate mechatronic system capable of interacting with the queen without being rejected or attacked by the court bees, which protect and nourish the queen.

This paper presents the results obtained in the first stage of an EU project motivated by the mentioned objectives for robot-queen honeybee interaction. This project includes the design and development procedure for a heterogeneous multi-agent robotic system capable of following the queen inside the observation hive and working around the queen like a court member for data collection and biological interactions such as feeding and pheromone transfer. The main contributions of this paper are listed as follows:

- Investigation of different approaches towards the robotic system design for delicate task accomplishment in a confined environment such as an observation hive.
- Propose a modular manipulation system in conjunction with semi-active operational agents to solve macro manipulation, micro-manipulation and robot-insect interaction criteria simultaneously

The remainder of this paper is organised as follows. In the second section, the main design challenges are demonstrated. The third section establishes the system design procedure for the robot and explains each subsystem's role. The mechanisms designed for the robot are introduced in the fourth section, and the fifth section presents the conclusion.

II. Design Challenges

The design procedure of delicate robots working in a harsh environment creates new challenges in the autonomous system area. The main challenges can be categorised as follows:

- The robots' workspace includes honeybees, intelligent species that become aggressive while confronting exogenous objects or phenomena. This condition requires recognising all the irritation sources like vibration, heat, collisions, etc.
- It is essential to eliminate the known irritation sources by maximising the robots' independence from the outside environment. Furthermore, considering the contactless approaches in order to increase self-management would be necessary, and it would be challenging to implement such approaches, especially in micro-level structures.
- The workspace around the queen is very tight, and the robots' movement should be delicate, precise, and agile to avoid undesirable collisions or hurting the queen while they perform their tasks. Therefore, the design procedure should consider high-precision approaches in construction and control to overcome this challenge.
- The hive condition should be protected from outside interference to remain stable for vital conditions such as temperature, humidity, and contamination level. This criterion implies using separation systems in approaches that enforce robots to rely on supportive elements outside the hive.
- The robots should work continuously for a considerable duration. This necessity raises a serious power supply challenge for robots. Accordingly, it is crucial to consider a highly efficient power supply and consumption system to manage the sustainability and energy waste in the form of heat, which causes the temperature increase and disturbs the hive's environmental stability.

All the mentioned challenges imply a substantial feasibility study on the current technologies and design methods to determine practical approaches to achieve the project's objectives.

III. Conceptual Design

The project's main objective is to keep the interactive parts of the system in the vicinity of the queen, considering a safe distance and following the desired trajectory related to the queen's reactions. Accordingly, the system should be capable of the following:

- Localisation of the queen to determine its position and orientation.
- Micro-manipulation of the interactive parts around the queen to place them in desired positions related to their tasks and avoid any collision with the queen or court bees.
- Macro-manipulation of the interactive parts and localisation system following the queen through the hive to cover all the areas where the queen goes normally.

According to these requirements, the suggested system includes four major subsystems:

1) A planar positioning system to manipulate the end effectors and interactive agents in a parallel plane to the observation hive.
2) An end-effector which includes independent mechanisms for micro-manipulation of each interactive agent independently.
3) Interactive agents manipulated by the end-effector around the queen to manage the interaction with it.
4) Localisation system is responsible for determining the location and orientation of the queen, court bees, and the interactive agents around the queen for control and management purposes.

In spite of all complexities, the modular design allows for reducing the complexity and cost significantly by dividing the manipulation tasks into two macro and micro levels. Nevertheless, it is necessary to consider compatibility criteria for every connected subsystem. For instance, the positioning accuracy and resolution for the macro-manipulation system are considered subsystem-level criteria. However, it is necessary to consider the weight and inertia tensor of the other modules attached to the mechanism to design the actuation system, which is implied by other subsystems (the end-effector and the localisation system) as a critical requirement.

A. *Macro-manipulation system*

This section describes the requirements and constraints for the design of the Macro-manipulation system, one of the main parts of the mechanical system that moves the end effector and camera subsystems. During the system's operation, the mechanism will track the queen bee based on the input from the camera subsystem. The End effector, which would carry out the interactions with the queen bee, will also be attached to this mechanism. For large-scale experimentation, it is necessary to produce a large number of (∼15) manipulation systems to achieve a system with reasonable cost. The following criteria are considered during the design procedure:

- The structure must be easily attachable to the observation hive.
- The mechanism must be precise in its movements to prevent harming the queen bee during the interaction.
- The camera distance should be adjustable to prevent the camera image from becoming blurry.
- The mechanism should move all the related subsystems during the interaction experiments that could run for days.
- The construction cost should be reasonable.

In [21], a plotter mechanism that can move in two axes was used to move the robot assembly in front of the hive was designed and manufactured. Since honeybee waggle dance has similar requirements to the RoboRoyale system, such as active workspace size, it can be concluded that this system may comply with the performance criteria of RoboRoyale.

B. *End-effector*

The end-effector is the second major part of the mechanical system. This part will be constructed for the support and motion management of the interactive agents. Also, it should be attached to the macro-manipulation system for the ultimate positioning to track the queen. On the other hand, it is necessary to consider supporting parts for the main camera and adaptors to handle the separation system. Although this part would be attached to the main structure, it is essential to consider enough space for electronic boards working to drive the sensors and actuators, and processing units necessary for local data analysis and command calculation. According to the small-size workspace considered for the operational agents around the queen, the end-effector should be capable of handling delicate and precise motion to prevent triggering aggressive behaviour in the hive or even hurting the queen. Similar manipulation systems are mostly utilised in cases that need to interact with fragile structures. For instance, Harvard University suggested to collect fragile samples by a multi-arm rotating mechanism with an elastic cage with shape controlled by the arms [22]. Although the target application for this robot seems different from fine manipulation in confined areas, the design technique utilised to integrate a rotating base and multiple independent arms to adjust the shape of the cage with the specimen's shape would be inspiring for the design procedure in the RoboRoyale project. Another technology that would be helpful and inspiring for the design procedure in this project is artificial hand technology. However, the complete design and control for an artificial hand would be more complex regarding the workplace requirements of this project. These robots would be inspiring, especially for actuation system selection, the kinematic modelling of the joints, and the control scheme for independent positioning [23]. Surgical robotics is a significant research area investigating robotic design for delicate manipulation in an extremely sensitive environment. Despite the complexity, there are lots of concepts and practical robots currently used in robotic surgery. [24] demonstrate different categories of surgical robots that utilise precise actuation and positioning systems with both passive and active mechanisms. In addition to the above articles, there are many other applications, such as a lab management unit presented by [25] for working in a fragile environment or other emerging multi-arm surgical robots, as illustrated in [26]. According to the surveyed available robotic design strategies and the project's criteria, the end-effector mechanism includes the following parts:

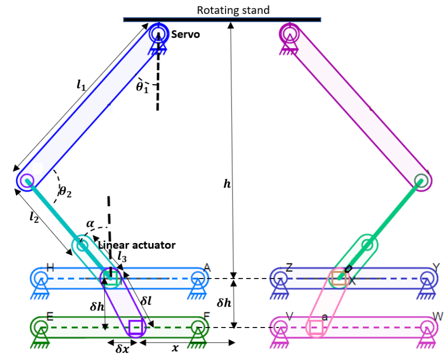

Fig. 2. The schematic view of the end-effector mechanism

- A rotating base to adjust the circular position around the queen.
- Linear actuators to control the radial distance from the centre of the mechanism occupied by the queen.
- A link between the linear actuator and the rotating stand which is capable of rotation to increase the travelling distance around the queen.

The schematic view of the mechanism is shown in Fig. 2 as follows: According to the geometrical parameters introduced in Fig. 2, the required rotation angle for the servo, θ_1, and the required translation for the linear actuator, l_3, can be obtained from Eq. 1 as follows:

$$\begin{aligned} l_3 &= \frac{1}{\cos(\alpha)}\left(h - l_1\cos(\theta_1)\right) - l_2 \\ \theta_1 &= \sin^{-1}\left(\frac{1}{l_1}\left(h\sin\alpha - (D - x - \delta x)\cos\alpha\right)\right) - \alpha \end{aligned} \quad (1)$$

where D is the horizontal distance between the centre of the rotating stand and the servo attachment position, and α is the adjustment angle for the linear actuator. The system is prevented from singularity considering $\alpha < \frac{\pi}{2}$. If the link between the linear actuator's head and the workspace plane (with the length of δl) is adjusted with the same angle as the linear actuator, then α could be evaluated by:

$$\cos\alpha = \frac{\delta h}{\delta l}, \quad (2)$$

where δh is the distance between the mechanism front plane and the operation plane in the observation hive. Although (1) can describe the relationship between the desired value of the end-point distance to the centre and the actuators' position, an open loop system can not guarantee a proper transient response and steady-state error regulation. Accordingly, it is necessary to consider a control policy to achieve the required operational performance. The suggested control policy utilised the second part of (1) as the input for the servo and (3) to drive the linear actuators and regulate the steady-state error.

$$\begin{aligned} l_3 = \tfrac{1}{\cos(\alpha)}\left(h - l_1\cos(\theta_1)\right) - l_2 + \\ + k_P e_x + k_I \int (e_x)dt + k_D \tfrac{d(e_x)}{dt} \end{aligned} \quad (3)$$

where $e_x = x_{des} - x$ is the tracking error for the desired central distance, and k_P, k_I, k_D are the controller gains that can be obtained with normal tuning procedures for PID controllers. The mechanism designed based on this configuration and the closed-loop response applying the suggested control policy are presented in Section V.

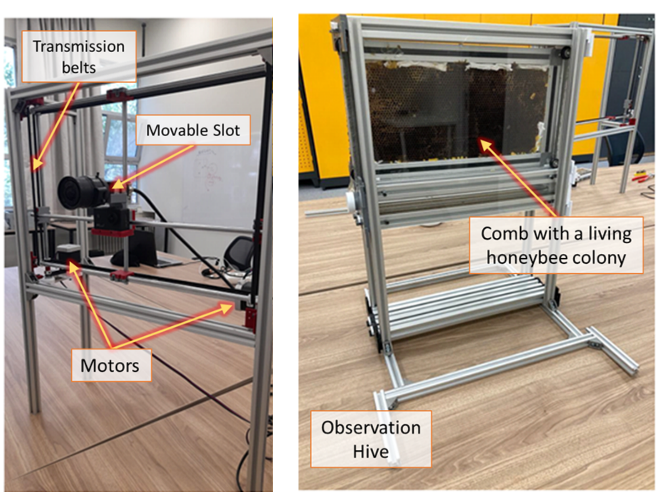

Fig. 3. (Left) The planar positioning system for macro manipulation. (Right) Observation hive with an inserted comb and honeybee colony.

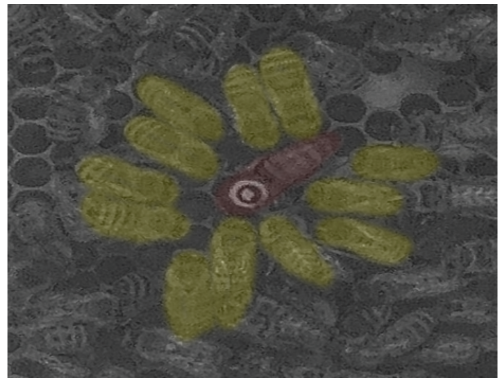

Fig. 4. Example court event detection result. Courtesy of [29].

IV. Monitoring the queen's vicinity

Monitoring the queen's immediate surroundings is essential to extract the queen's and the court bees' behaviours. To perform agent-queen interactions safely, these must be mimicked precisely with the operational agents. To achieve continuous monitoring, the queen's pose has to be estimated in real-time with high accuracy and reliability.

Thus, we have developed a vision-based tracking and integrated it into the Robot Operating System (ROS), providing easy interoperability with the rest of the mechatronic system. Apart from calculating the queen's position, the system also provides high-resolution continuous imagery of the queen's vicinity, which is then processed to provide the positions of the court bees interacting with the queen.

A. Queen detection

Using images captured in the early stage of the project, we investigated the performance of marker-less and marker-based bee tracking algorithms [27]–[30]. Based on our investigations, we focused on the use of fiducial markers, such as AprilTag [31], ArUco [32], and WhyCode [33]. The deployed system uses a fiducial marker attached to the queen's thorax, detected and tracked by the WhyCode method [34], [35]. This method can deal with the small size of the tag (12-17 pixels in width) while maintaining real-time performance. To deal with occlusions caused by the worker bees cleaning the queen, the method incorporated an additional algorithm based on an adaptive convolutional kernel, resulting in a method called WhyComb [36].

B. Court bees detection

Once the queen's position is estimated, the system provides a cut-out image of the queen's vicinity. This image is subsequently analysed to extract the poses of the worker bees relative to the queen. We can determine which of the bees interact with the queen based on further analysis of these poses over time. Currently, the images are processed by the methods presented in [37]–[39] and their performance in court bee detection and localisation is investigated in [29]. A preliminary result of the court detection is shown in Fig. 4.

V. RESULTS

The main results obtained for the conceptual design are presented in this section. The macro-manipulation system is designed based on a 2-DoF mechanism that includes pulleys and a timing belt for linear motion control. Also, the mechanism designed for the end-effector is presented in Fig. 1. To test the mechanisms and collect data for further development phases, two simple prototypes were built: the first one to evaluate the macro-manipulation system and the second one to verify the performance of the rotating base and linear actuators. The first prototype constructed for the planar positioning is depicted in Fig. 3.

The simple test bed constructed to evaluate the rotating base mechanism and the linear actuators is shown in Fig. 5.

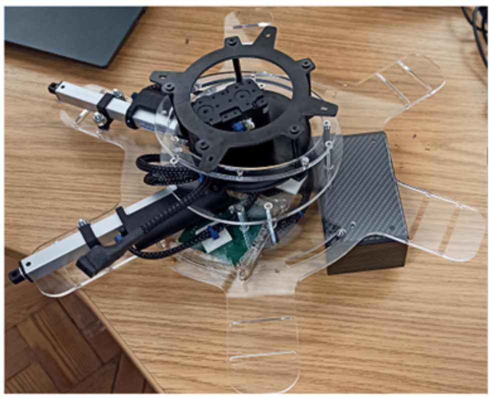

Fig. 5. First stage prototype to evaluate the rotating base mechanism and the linear actuators' performance

The planar positioning system, controlled by the honeybee queen tracking, was installed at an observation hive with a live honeybee colony. Over the course of a week, the system scanned the hive and actively tracked the queen, travelling over 500 m and obtaining over 200 000 high-resolution (0.03 mm/pixel) images capturing her interactions with the worker bees, see an example in Fig. 6.

A simulation environment is developed to evaluate the performance of the mechanism designed for the end-effector. In this simulation, the dynamic response of the servos and linear actuators are considered. The closed-loop system response for one arm is presented in Fig. 7.

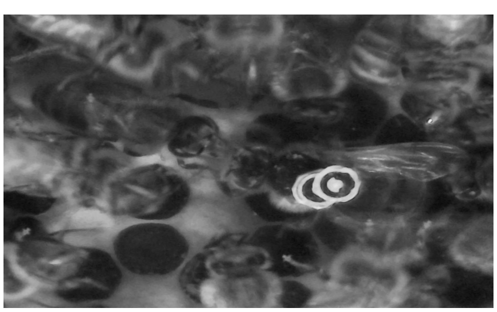

Fig. 6. Example image of the honeybee queen interacting with a worker bee

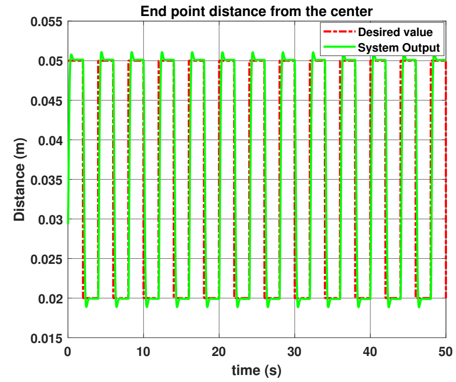

Fig. 7. Closed-loop output the end effector arms regarding the desired value for endpoint distance from the centre.

According to Fig. 7, the designed system follows the desired values accurately with reasonable transient and steady-state response. Furthermore, Fig. 8 demonstrates the actuators' outputs regarding the controller applied to the system to regulate the steady state error and improve the transient response characteristics.

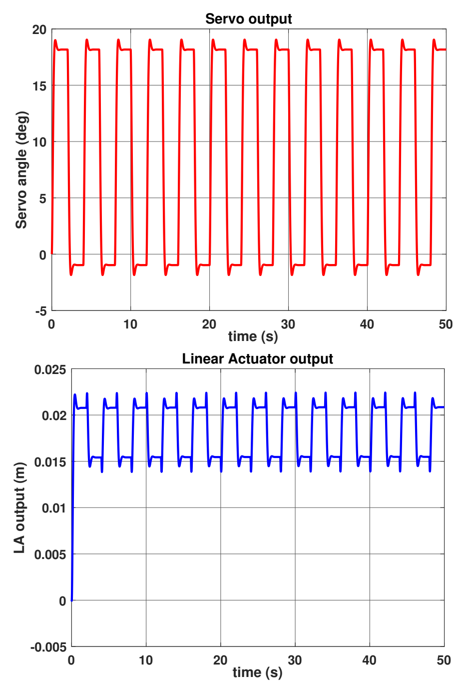

Fig. 8. Actuators' output regarding the applied control policy

VI. CONCLUSION

This paper includes the first stage of the design procedure for the RoboRoyale project's robotic system. Different approaches are considered toward the robot design. In order to reduce the complexity and construction cost, a modular approach toward the mechanical design is considered to make the design procedure straightforward and allow fast prototyping for both control system development and biological test conduction purposes. Although this attitude toward the robot design results in a system with a physical connection between the parts inside the hive and the supporting units outside the hive, it allows for making a system with simple technological requirements. Therefore, it is possible to have a complete system that works properly for data collection and test conduction in conjunction with the observation hive. Furthermore, the preliminary results for the vision system design and development are presented in this paper. The vision system is working actively now, and a rich database is created in order to behavioural study the queen and its court and also to improve the tracking system which will be used as the main part of the feedback system for the robots to realise their relative position with respect to the queen and move precisely around it.

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