POLITECNICO DI TORINO

Master's Degree in Mechatronic Engineering

Master's Degree Thesis

Cyborg Insects as Biohybrid Robots: Experimental Modeling and Sliding Mode Control

Supervisors

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Abstract

The concept of Cyborg Insects has attracted considerable attention in recent years due to their great potential in various fields such as agriculture, surveillance and rescue operations. Thanks to the improvements in technology and the reduction in the size of electronic components, new frontiers have opened up in the study of these systems. More recent research involves integrating electronics and sensors onto the bodies of insects (in this research, Madagascar Hissing Cockroaches) to allow remote control of their movements, trajectories and behaviors. A combination of microelectronics and neuro-engineering techniques is used to achieve this integration, including wireless communication systems, miniaturized sensors and neural interfaces. Due to their small size and ease of programming, these cybernetic systems could represent a better alternative to regular micro-robots, as the latter may take longer to program and would likely have difficulty moving in confined spaces and rough terrain.

The research activity for this thesis comprehensively explores different types of electrical stimulation of the cyborg insect, studying the concept of habituation to stimuli and methods to avoid it. This is done by analyzing the effect of changing different parameters in the electrical signals provided as input to the hybrid robot. The second part of the activity is dedicated to finding a kinematic mathematical model capable of describing the behavior of a real cockroach in response to electrical stimulations taking into account its non-linearities. The model obtained is then implemented in MATLAB/Simulink. A Sliding Mode Control algorithm is designed and applied for tracking the trajectory of the cyborg insect, improving motion planning and showing very promising results for the applicability of the Variable Structure Control strategies in living systems such as cockroaches. The research activity of the thesis led to the publication of two conference papers and one article in an IEEE international journal. In particular, the results regarding experiments and modeling were presented at the 41st Annual Conference of the Robotics Society of Japan (RSJ 2023), September 11-14, 2023, Sendai International Center, Miyagi

Prefecture and the paper was published in the conference proceedings. The results about Variable Structure Control for Cyborg Cockroaches were published in a paper in the IEEE Control Systems Letters, 2023, and will be presented at the 2024 American Control Conference (ACC 2024), July 8-12, 2024, Toronto, Canada, the paper will also be published in the conference proceedings (joint submission ACC 2024 and IEEE L-CSS).

Keywords: Cyborg Insects, Biohybrid Robotics, Experimental Modeling, Variable Structures Systems, Sliding Mode Control, Nonlinear Control.

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Chapter 1

Introduction

For my exchange semester in Japan, I was honored to be part of Professor *Keisuke Morishima*'s Lab "LiveMechX" in Osaka University: a research environment where different subjects coexist synergically, ranging from Biology to Mechatronics to Micro and Nano-Manufacturing. One of the research projects that the team at Morishima Lab is carrying out is the Cyborg Insect (CI) for search and rescue missions. This research is part of a governmental megaproject and funding institution called *Moonshot project*.

1.1 Moonshot Project

The Moonshot project in Japan is a government-led research initiative aimed at accelerating innovation in science and technology. This activity, officially called the "Moonshot Research and Development Program," was launched in July 2020, with a budget of 100 billion yen (673 million euros) for the first year.

The aim of the Moonshot project is to bring together researchers from different fields, including engineering, physics, biology, and information technology, to work on innovative solutions to some of the world's most pressing challenges. The focus is on ambitious and transformative projects that can make a significant impact on society, such as developing new technologies for clean energy, tackling climate change, and improving healthcare.

The Moonshot project is structured around nine "moonshots" or ambitious goals. These include creating a carbon-neutral society by 2050, developing an ultra-efficient quantum computing system, achieving personalized cancer immunotherapy, establishing a society that can coexist with nature and AI, extending healthy life expectancy over 100 years old and more [2].

The project has attracted significant attention and support from both the Japanese government and private sector. It is seen as a way to foster innovation, create new industries, and position Japan as a global leader in science and technology.

LiveMechX lab is on the forefront of this project, with the research being part of Goal number 3: "Coevolution of AI and Robots". Professor Keisuke Morishima's project is called *"New World of Inspiration by Co-evolution of Humans, AI Robots, and Biological Cyborgs"* which on the official website of the project is described in this way: *"By analyzing activity information and surrounding environment information obtained from a group of biological cyborgs equipped with ultra-small sensors, communication equipment and behavior control units, we will understand the principles of action and use them to develop a self-organizing platform using AI that stimulates human behavior and enables people and robots to collaborate without any sense of incongruity. By 2050, we aim to create a world where people and robots can work in harmony with each other"*[2].

Overall, the Moonshot project is a bold and ambitious initiative that aims to tackle some of the world's most pressing challenges by fostering collaboration and innovation in science and technology.

1.2 Thesis Activity and Original Contributions

CI systems have often been proposed as an alternative to standard robots for a number of reasons. They are easier to design since they do not require lengthy and precise programming and modelling of their movements. They are more efficient, since in order to work properly they only have to use power for the stimulation and sensing devices, instead of also using it for the actuators needed to move around. It has been calculated that a cyborg insect can be more than a thousand times more power-efficient than their human-built counterparts, [12]. Typically, these systems consist of a living insect equipped with a microcontroller that serves as a means of communication between the user and the insect itself. The microcontroller facilitates receiving stimulation signals from the user and acts as a platform for sensors that gather information from the surrounding environment. In my research and experimental activity with the Morishima Lab team, we worked with Madagascar Hissing Cockroaches (MHC) as they are optimal for cyborg insect studies due to their ability to carry the weight of relatively complex hardware and a heavy battery. These cyborg systems can be especially useful in environments where it is difficult for humans or other small robots to work in, such as rescue missions in disaster-stricken areas.

The stimulation methods constitute one of the most crucial areas of research of the CI systems. The first phase of my activity was devoted to explore the potential of different electrical stimulation patterns in enhancing the locomotion capabilities of cyborg cockroaches. Through experiments we compared different voltages and frequencies, as well as the use of biphasic and monophasic signals, trying to increase the repeatability of the experiments.

CIs are rapidly becoming the frontier in research into alternative robotic systems since they are particularly suitable for applications where it is necessary to move in unstructured environments, however it is still difficult to precisely model their movements due to the highly nonlinear behavior of biological systems compared to engineered robots. The second fundamental phase of my experimental activity was aimed at modelling of CIs. The equations describing the behavior of the cyborg cockroach were obtained by carrying out experiments. The MHC-specific kinematic mathematical model constitutes a new result in the relevant literature.

The final phase of my activity was dedicated to study and design a controller for CIs. Indeed, for these bio-systems the use of automatic control has not been widely investigated in the literature. Interesting results can be found regarding the teleoperation of cyborg cockroaches where the insect is controlled remotely by a human operator who monitors the cyborg's movements captured live by a webcam, [3], [31], or concerning an automatic control first approach to maintain the insect moving in a delimited arena (without trajectory tracking) where the stimulation of the cerci is applied every time a stop of the cockroach is detected, [4]. Applying a first-order sliding mode control to a cyborg cockroach to perform desired trajectory tracking is itself an important novelty. The proposed model of the CI was used as the basis to design the control approach.

The research activity of the thesis led to the publication of two conference papers and one journal article.

Paper in the Proceedings of the Robotics Society of Japan Conference, 2023

During my stay at Osaka University a first paper was written with the results regarding experiments and modelling. It appears in the Proceedings of *the 41st Annual Conference of the Robotics Society of Japan (RSJ 2023)*[1], September 11-14, 2023, Sendai International Center, Miyagi Prefecture, Japan. I presented the paper on September 12th in Sendai, Japan. The title of the paper is *"Experimental Movement Analysis of Cyborg Cockroaches via Electrical Stimulation Patterns"*, [11], by A. Caforio, C.M.M. Refat, M. Ariyanto, K. Yamamoto, E. Punta, and K. Morishima. The contents of this paper are discussed in Chapter 4.

Journal Paper Published in IEEE Control System Letters, 2023

The second paper was written with the results about Variable Structure Control for Cyborg Cockroaches during my stay in Osaka University. It was published in the *IEEE Control System Letters* journal, 2023, and will be presented at the *2024 American Control Conference (ACC 2024)*[2], July 8-12, 2024, Toronto, Canada. The paper will also appear in the conference proceedings (joint submission ACC 2024 and IEEE L-CSS). The title is *"Enhancing Cyborg Cockroaches Behavior through Experimental Modelling and Variable Structure Control"*, [10], by A. Caforio, E. Punta and K. Morishima. The contents of the paper are discussed in Chapter 6.

[1]This domestic conference is organized by the prestigious *Robotics Society of Japan (RSJ)*, founded with the aim to facilitate and spread the development of research and knowledge of robotics and to promote the growth of Japanese academics in this field.

[2]ACC is the annual conference of the American Automatic Control Council (AACC), the U.S. national member organization of the International Federation for Automatic Control (IFAC). National and international society co-sponsors of ACC include the American Institute of Aeronautics and Astronautics (AIAA), American Institute of Chemical Engineers (AIChE), American Society of Civil Engineers (ASCE), American Society of Mechanical Engineers (ASME), IEEE Control Systems Society (IEEE-CSS), Institute for Operations Research and the Management Sciences (INFORMS), International Society of Automation (ISA), Society for Modeling & Simulation International (SCS), and Society for Industrial & Applied Mathematics (SIAM).

1.3 Research Goals

The underlying motivation for this Master's thesis was to explore the theory behind Cyber Organisms and Electrical Neural Stimulation trying to find answers to the following questions:

- What is the most suitable Electrical Signal that we can use to stimulate CIs?
- How can we avoid habituation to stimuli?
- Is it possible to Model the behavior of a living system given a set of inputs?
- Can we increase the accuracy of trajectory planning of the CIs using some nonlinear control strategy?

1.4 Thesis Outline

After this introductory chapter, the thesis first presents the background of the research sector relating to Cyborg Insects and then goes into detail on the various phases of my research activity as well as on the results obtained during my exchange period at LiveMechX Lab. The thesis is structured in chapters as follows:

- **Cyborg Insect Theory** introduces the scientific background on CIs and the experimental findings of previous research on the topic.
- **Electrical Stimulation Theory** provides a brief review of works and results on electrical stimulation and related issues presented in the relevant literature.
- **Study of Electrical Stimulation on the Cyborg Insects** describes the tests conducted to find the correlation between different waveform parameters and the response of the CIs.
- **Experimental Modelling of the Cockroach** presents the experiments performed to find the MHC-specific kinematic model.
- **Sliding Mode Control for Cyborg Cockroach** proposes the design and application of SMC to the MHC to achieve desired trajectory tracking.

- **Conclusions** offers some concluding considerations on the results obtained from this thesis and on possible future developments.

Chapter 2

Cyborg Insect Theory

2.1 What is a Cyborg?

The term *Cyborg*, short for cybernetic organism, refers to an entity that integrates both organic and artificial components, often with the intention of augmenting or enhancing the natural capabilities of the original organism. The idea of the cyborg challenges traditional binaries of nature versus technology. At its core, the concept of the cyborg is emblematic of humanity's desire to transcend its biological limitations, blurring the lines between man-made and natural, and between biological and mechanical.

The term *Cyborg* was first coined by Manfred Clynes and Nathan Kline in 1960, in a scientific paper titled "Cyborgs and Space" [13].

There exist several fascinating variants of the cyborg concept, each with its unique intricacies and challenges:

1. **Human Cyborgs:** This is the most widely recognized form of cyborg. Typically, when people think of a cyborg, they envision a human being with integrated technological components, be it prosthetic limbs that respond to neural inputs, implantable devices to enhance sensory capabilities, or even brain-computer interfaces that allow direct communication between the human brain and external devices. Cochlear implants, for example, which convert sound into electrical signals that are sent directly to the auditory nerve, are a modern example of a technology that turns its user into a form of cyborg.

Furthermore, with ongoing research in areas like neuralink technology, the prospect of achieving seamless integration between the human mind and machines is becoming more tangible.

2. **Plant Cyborgs:** Perhaps a less well-known category, plant cyborgs involve the fusion of plants with electronic components. Research in this area has been inspired by the remarkable ways in which plants respond to their environment – for instance, their roots seek water, and their leaves orient toward sunlight. By integrating sensors and circuitry with plants, scientists are attempting to harness these natural responses for various applications. For example, there is research on plants with integrated circuits that could detect specific environmental contaminants or changes, thereby serving as bio-monitors [18].

3. **Insect Cyborgs:** This involves the melding of live insects with electronic components. In this research, different variants of CIs will be presented. These insect cyborgs have potential applications in areas like environmental monitoring, search and rescue operations, and even military surveillance, capitalizing on their natural abilities to navigate challenging terrains and environments.

The burgeoning interest and investment in the field of cyborg technology is emblematic of its paramount importance in the contemporary scientific landscape. Several driving forces underpin this significance:

- **Medical Rehabilitation and Enhancement:** One of the primary areas where cyborg technology has shown promise is in medical prosthetics and rehabilitation. For individuals with disabilities or those who have suffered traumatic injuries, cyborg enhancements offer the hope of restoring lost functions, be it mobility, hearing, or even sight.

- **Exploration and Adaptation:** Cyborg enhancements could play a pivotal role in helping humans adapt to extreme environments, such as deep-sea exploration or even space missions. By integrating with machines, humans may overcome some of the biological limitations that make these environments inhospitable.

- **Human-Machine Collaboration:** In an era characterized by rapid technological advancement, the fusion of humans and machines can facilitate more intuitive and efficient interactions, be it in the realm of work, entertainment, or daily life[18].

However, the march of cyborg technology is not without its challenges. Ethical concerns abound, especially when it comes to potential socio-economic disparities in access to enhancements, the possibility of creating "superhumans" with augmented abilities, and questions about autonomy, identity, and what it means to be human.

In conclusion, the realm of cyborgs – spanning from human and insect to plant variants – represents a nexus of biology, technology, and ethics. Its importance in today's scientific world cannot be understated, offering transformative applications while simultaneously posing profound philosophical and societal questions. As we stand on the cusp of an era where the lines between the organic and artificial continue to blur, it is wise for us to proceed cautiously, ensuring that our cyborg future is shaped by considerations of equity, humanity, and shared benefit.

2.2 Cyborg Insects at Morishima Lab

In the next chapter I will be exploring a CI design that was thought of and is currently being refined and worked upon in the *"LiveMechX"* lab in Osaka University. This section will be referring mainly to the previous research conducted by my colleagues in the Lab: Mr. *Mochammad Ariyanto*, Mr. *C.M. Masum Refat*, Mr. *Kazuyoshi Hirao* and Professor *Keisuke Morishima*.

It is important to specify that this is by far not the only existent design, and that many other CI projects exist in research laboratories across the world.

2.2.1 MHC Anatomy and Behavior

The Madagascar Hissing Cockroach (MHC) (Gromphadorhina portentosa) is a large, flightless insect that is native to the island of Madagascar. Despite its name, this species of cockroach is not considered a pest and is often kept as a pet or used in educational settings due to its unique characteristics and ease of care. In this section, I will shortly describe the anatomy of the MHC, to be able to understand the following sections more easily.

The exoskeleton of the MHC is made up of chitin, a tough, opaque and semi-reflective material that provides protection and support for the insect's internal organs. The exoskeleton is divided into three main parts: the head, thorax, and abdomen [16].

The head of the MHC is triangular in shape and contains the insect's eyes, antennae, and mouthparts. The eyes are compound, which means that they are made up of many individual lenses that allow the insect to see a wide range of angles and detect movement. The antennae are used for sensing the environment and detecting chemicals such as pheromones. The mouthparts of the MHC are adapted for chewing and grinding food, and include a pair of mandibles, maxillae, and labium [16].

The thorax of the MHC is the middle section of the insect's body and contains a set of legs. Without the presence of wings or tegmina, the thorax of the cockroach is relatively small compared to other species of cockroach. The legs are well developed and adapted for running and climbing, with spines and hooks that provide traction and grip on surfaces.

The abdomen of the MHC is the largest section of its body and contains the digestive, reproductive, and excretory systems. The digestive system consists of a long, coiled tube called the gut, which runs the length of the abdomen and is divided into several sections. The gut is lined with cells that secrete enzymes to break down food, and absorbs nutrients and water from the digested material. At the extreme end of the abdomen, the cockroach has another pair of sensing organs called *cerci* (singular *cercus*) [16].

The reproductive system of the MHC consists of both male and female organs, and fertilization occurs internally. Females lay their eggs in capsules called ootheca, which are then incubated until they hatch into nymphs. The excretory system of this particular species of Cockroach consists of a series of tubes called Malpighian tubules, which remove waste products from the insect's body and release them into the gut to be eliminated.

There are some striking differences between the sexes. Males possess large horns on the pronotum, which is the central section of the thorax while females have only small 'bumps'. The presence or absence of the pronotal horns allows easy identification of the sexes. The antennae of males are hairy while the antennae of females are relatively smooth. Finally, the behavior of males and females also differ: almost only males are aggressive.

In addition to its internal organs, the MHC has several external structures that are important for its survival. The feet are equipped with tiny sensory hairs that allow the insect to detect vibrations and changes in the environment. Finally, this species has the unique ability among insects of being able to communicate using modified spiracles on its abdomen. Most other invertebrates communicate by stridulation, rubbing body parts together, while MHCs instead, force air through the respiratory spiracles so that a hiss is emitted, which serves as an auditory social signal [25]. A picture of the whole MHC is shown in Fig. 2.1.

Fig. 2.1 Picture of a female Madagascar Hissing Cockroach [1]

The aggressive encounters between male MHCs are noteworthy, involving the use of their heads and abdomens to push and ram into each other. The larger male is typically victorious, indicating the significance of size in determining dominance. During these confrontations, hissing plays a critical role. The winning male generally produces more hisses than the defeated opponent, suggesting that hissing may be a signal of aggression and dominance. Additionally, the hisses contain information about the male's size, which the opponent can use to evaluate their strength. Males are also capable of distinguishing between the hisses of familiar and unfamiliar individuals, implying that they possess a degree of social recognition. These audible hisses may be used for communication and social behavior, and the observation that males may fight during the day despite being primarily nocturnal indicates that other factors may influence their social behavior. Overall, the behavior of male Madagascar hissing cockroaches demonstrates complex social interactions that may indicate a more intricate social structure than previously believed.

To summarize, the different hisses produced can be cataloged into 3 distinct kinds: aggression, courtship and disturbance.

- The aggression hiss is displayed by the male during agonistic encounters which form hierarchies within the colony.
- The courtship hiss is again only displayed by males and is essential for successful mating. It is thought that females may use the hiss to elicit preference in mating by choosing larger, more dominant males.
- The third type of hiss, the disturbance hiss, is easily identifiable from the others as it is both the loudest in amplitude and shortest in frequency. This hiss is classified as an anti-predatory response and is displayed by all members of this species past around 4 months of age [25].

2.2.2 Stimulation on the MHC

The MHC species of cockroaches, as has already been mentioned, has two pairs of antennae that are attached to the head in the front and two cerci that are attached to the abdomen in the back. With regards to the antennae, MHCs respond to tactile stimuli by turning in the opposite direction (turning right if the left antenna is stimulated and turning left if the right antenna is stimulated) [14]; with regards to the cerci instead, they produce a forward motion with a slight turn in the direction opposite to the cercus that has been stimulated.

Theoretically, many different media can be used to stimulate CIs. Numerous studies have demonstrated that the majority of cockroach species are capable of responding to both chemical and vibrational stimuli [11], and, although less popular, also to stimulation done with light. The most popular stimulation medium, by far, is electricity. Electrical stimulations are usually applied via electrodes implanted in the

Table 2.1 Reaction of the MHC to electrical stimulation

Stimulated port	Reaction
Right Cerci	Go Foward with a slight left turn
Left Cerci	Go Foward with a slight right turn
Right Antenna	Stop the motion and Start rotating counter-clockwise
Left Antenna	Stop the motion and Start rotating clockwise

antennae and cerci of the organism, which mimic the natural mechanisms within the sense organs.

Since this species of cockroach can navigate its surroundings by scanning the obstacles around itself (touching them with the antennae), the artificial stimulation methods would ideally look like something as similar as possible to this mechanism. In our case, the electrical signals that are provided to the animal fundamentally trick its brain into thinking that the antennae or cerci have come in contact with an object. The cockroach, depending on which of the 4 stimulation "ports" has been provided with an electric signal, reacts in different ways that are summarized in Table 2.1.

2.2.3 Surgery Procedure

Prior to being able to be used as a Biological robot, the MHC has to go through a small surgery in order to be able to interface with the Hardware that will be mounted on top. The surgery procedure will be explained in detail in this section.

Before surgery, the cockroaches live in small colonies of around 25/30. They are divided between male and female, they are all provided with food and the containers are cleaned weekly. They are kept in a controlled dark room with set temperature and humidity and the boxes are filled with cardboard sheets to simulate spaces where they can crawl and hide as they would in their natural habitat.

The Cockroaches get selected based on weight, sex and dimensions. Usually a good candidate for surgery is a Cockroach in its full adult stage with a large enough size to be able to carry the Hardware Backpack on its thorax. Furthermore, another discriminatory element to consider is the dimension of the antennas and cerci: if the cockroach is too small, the cerci may be too difficult to do surgery on, or they also may be inside the body. Normally, female cockroaches are larger than their male counterparts, so they tend to be more suitable; furthermore, they are more prone to not show aggressive behavior towards the handlers and they also have a smoother thorax, with smaller pronota, so it's easier to attach the hardware piece on it.

When the cockroaches have been selected they go through a process of total anesthesia. To do this, they get put in a container with CO_2 and left there for roughly 1 minute. After the CO_2 anesthesia, they will be asleep for around 5 minutes, and in an analgesic state for another 10 to 15 minutes. To slow down the waking process, during the surgery, the cockroaches are periodically put in an ice bath [7][8].

Once they are asleep, depending on the type of experiments that they will be performing, different kinds of surgeries can be done. In this section I will explain the full surgery that is done for the experiments with the electronic backpack. At first, the tips of the antennas are cut off at around 1 cm. To interface with the nervous system of the biobot, a small piece of platinum wire from *A-M systems* is used and is inserted roughly 3 mm inside the sensory organ. The platinum wire has a teflon coating that has to be burned off with a lighter. The electrode is then linked to regular copper wire that will be connected to the rest of the hardware system of the biobot. The cerci receive a similar treatment, the only difference is the length at which they are cut: being smaller organs, only around 1 mm is cut off and the platinum electrode is inserted at the same distance [3].

In order for the circuit to work, it has to be grounded. To do this, we link the positive wire from the antennas and cerci to the Hardware part that will generate the stimulation signals and then poke a very small hole in the thorax of the MHC, This hole in the thorax will act as a ground connection, which will close the circuit attaching the negative electrode. The hole has to be done near the midline of the thorax at a depth of around 3mm [3]. Fig. 2.2 shows a picture of the cockroach that has undergone surgery.

Fig. 2.2 MHC that has undergone surgery on both antennae and cerci

To power the biobot, a lithium polymer (LiPo) battery with a 50 mAh capacity is chosen because it is relatively lightweight (1.4 g) and can supply power for more than 50 min. The weight of the latest version of the electronic backpack is 7 g, which is a weight that an adult cockroach can easily carry.

After the surgery, the biobots are woken up and left to rest for at least 24 hours in another separate container, away from the other non-modified cockroaches. Something to keep in mind is that the connections done with the wires have to be the tightest possible, since even the smallest amount of loose wires can create a way for the cockroach to try and remove the apparatus, by scratching itself with its legs and ramming towards the walls of the container, with the risk of damaging both the hardware and injuring itself. To prevent this, the antennas are also glued to the pronotum (on the thorax).

2.2.4 Hardware of the Cyborg Insect: the Backpack

This section will deal with the description of the "cyber” part of the CI; to control the behavior and receive data from the biobot, we need some kind of sensing equipment and stimulation apparatus to respectively receive data about the environment and give commands to move or do other actions to the organism. To do this, researchers at LiveMechX Lab have developed different versions of a “backpack” to contain all the electronics needed for the previously described problems.

The key component of the system is the *Seeduino XIAO microcontroller* from Seeed Studio, which serves as the main computational unit for the backpack. It utilizes *ARM Cortex-M0+ CPU* (SAMD21G18) running at up to 48 MHz. The board size is 20 mm in length and 17.5 mm in width, making it suitable for the CI backpack. This microcontroller is powerful enough to handle the complex data processing required to collect and analyze data from the sensors. It is also compatible with the Arduino IDE programming language, making it easy to program and customize [3].

The wireless transceiver used in the project is the NRF24L01 surface mount device 2.4-GHz wireless module from Nordic Semiconductor. It allows data to be transmitted wirelessly from the backpack to a remote computer and vice-versa. It enables the user to both monitor and control the cockroach’s movements and behavior in real-time and also to receive real time data about the environment it finds itself in. This latter capacity is of vital importance since it is also the only way that we can receive data about the true intentions of the living organism behind the cyborg [3].

The backpack is also equipped with a range of sensors that differ depending on the version of the backpack, here is a list of those present in the latest published version of the backpack model [3]:

1. The GY-955 is a 9-degree of freedom tracking device that includes a 16 bit 3-axis gyroscope, a 14 bit 3-axis accelerometer, a 3-axis magnetometer and a 32-bit microprocessor. This sensor is used to measure the cockroach’s kinematics, including respectively: its orientation, acceleration, and rotation. A built-in Kalman filter processes the sensor output for estimated attitude angles of roll, pitch, and yaw.

2. The BMP280 is a barometric pressure sensor that measures the atmospheric pressure and ambient temperature around the cockroach.

To integrate these components seamlessly, a custom surface mount device board was developed. This board allows for efficient communication between the microcontroller and the wireless module, making it easy to transmit data wirelessly from the backpack to a remote computer. The most crucial point was to obtain a compact backpack that would not hinder the cockroach movements and that could be as comfortable as possible, to avoid any disturbances in the data given by the discomfort of the cockroach. The backpack described in this section is shown in Fig. 2.3.

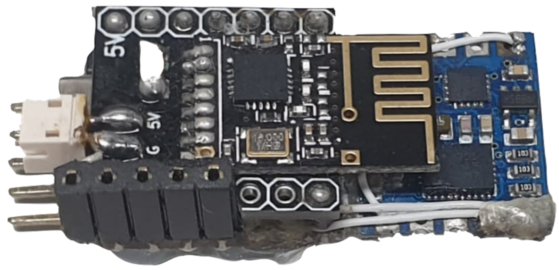

Fig. 2.3 Backpack mounted on the MHC [4]

The project's ultimate goal is to classify the cockroach's movements online using measured accelerations and angular rates from the accelerometer and gyroscope. To stimulate the cockroach, a 50-Hz pulse width modulation signal with a 50% duty cycle was generated using a custom interrupt service routine function under Arduino programming. This allows the user to control the cockroach's movements and behavior with precision, enabling them to study its responses to various stimuli.

2.2.5 Software of the Cyborg Insect

Compared to a classical robot, the software needed for modern day CIs is of relatively low complexity, since most of the decision making is processed by the brain of the living organism.

To allow the user and the CI to communicate, a User Interface (UI) is designed. The UI depends usually on the experiments that the CI will perform. In this section, I will describe the functionalities of a very basic UI that could potentially be used for any experiments, if modified according to the specific needs of the researcher. An example of software UI is shown in Fig. 2.4.

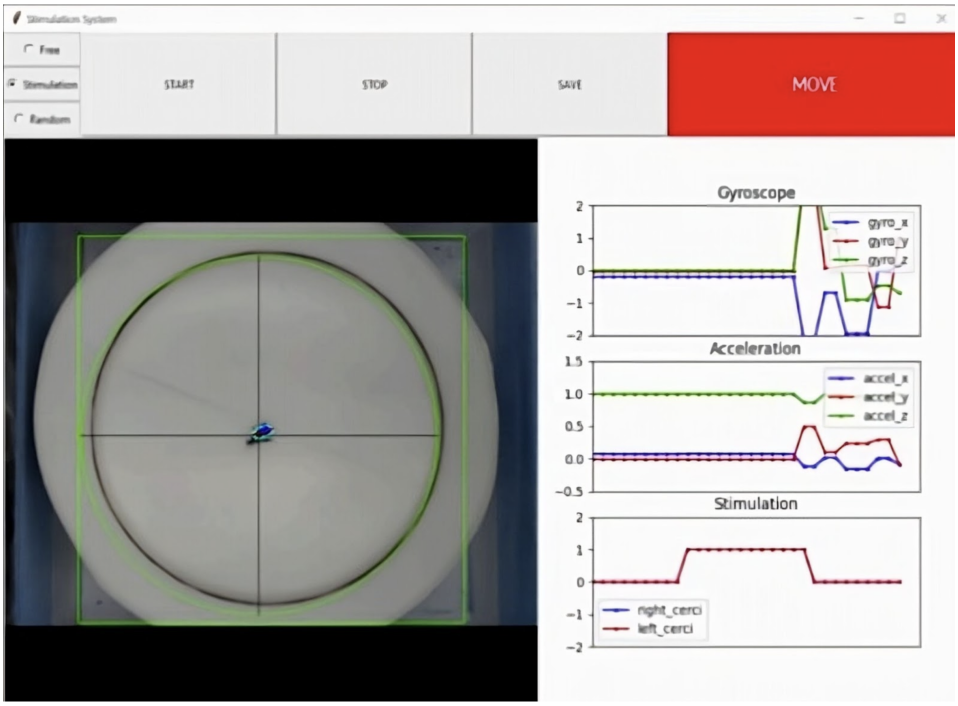

Fig. 2.4 Developed software UI to communicate with the cyborg [4]

The UI in Fig. 2.4 shows a top section with the possible commands to send to the wireless receiver:

- Start and Stop: to Initiate and End the Stimulation program.
- Save: To Save the generated charts.
- Move: To stimulate the cockroach; an additional section could be easily added to select which part of the body should be stimulated.

The UI also has a section on the right which shows the data collected online through the backpack installed on the cockroach. On the left instead, we can see a live view of the experimental testbed, obtained through a webcam installed on top of it.

As already stated, this UI was designed for a specific experiment and it is not useful for every type of test. In Chapter 4.1 there is a detailed description of the software related to the experimentation on the different types of electrical stimulation that was performed for this thesis.

2.3 Previous Experiments in the Literature

In this chapter two papers are summarized regarding the cyborg cockroaches in the LiveMechX lab at Osaka University. These papers are included in this section since they paint a good picture of the areas of research that the different teams studying these kinds of systems are currently exploring. Specifically, a research project which uses ML techniques to optimize the movement of CIs will be described; secondly, another project which explains how to control a cyborg cockroach telematically through an internet connection will be shown.

2.3.1 Movement Optimization Incorporating Machine Learning

This research paper [4] was aimed at optimizing the movement of CIs using *Machine Learning* (ML) techniques. To achieve this, the underlying methodology is to measure the trajectories of the CIs, understanding if the CIs are moving or they are still. If they are not moving, we can send a stimulation impulse to the cockroach through a controller to make it initiate the motion.

In this study, the biobot was composed of a cockroach with implanted electrodes in the two cerci and two antennae. The electrodes were connected to the hardware backpack, cockroaches were introduced in a circular arena and the behavior underlying their movement in a finite space was quantified accurately.

To show the results of the Machine Learning algorithm, a new term was introduced: the search rate. First of all, the test bed was divided into a known number of square grids. The search rate ε is calculated on the basis of the ratio of the number of grids searched within the experiment time to the overall number of grids inside a circular bounded space. The search rate is expressed in (2.1).

$$\varepsilon = \frac{grid_{searched}}{grid_{arena}} \tag{2.1}$$

In other words, an increase in the search rate means that a larger area can be searched, which can be said to be a more efficient search for the cockroach [4]. The goal was to increase the search rate and distance traveled by the cockroaches while reducing their stop time. To achieve this, the custom electronic backpack and wireless transceiver described in Chapter 2.2 was used, which allowed the researchers to stimulate the cerci of the cockroach and trigger its free walking motion.

To increase the search rate, a set of machine learning classifiers was trained to recognize specific patterns in the cockroach's movement that indicated it was not searching efficiently. When these patterns were detected, the system automatically stimulated the cerci of the cockroach to trigger its free walking motion, which allowed it to cover more ground and search more efficiently.

As for the choice ML algorithm, ten time-domain ones were chosen as classifier inputs and implemented the highest performing classifiers for online motion recognition and automatic stimulation.

To facilitate an interactive and intuitive interface between the desktop PC and cyborg cockroach in a circular bounded space, the custom *User Interface* (UI) described in Chapter 2.2 was used. This UI interface was built on Python with the Tkinter library. The UI managed all aspects of our computational system, including computer vision, data acquisition, stimulation command, feature extraction, and machine learning classification. The research also implemented a multithreading algorithm under the threading library in Python programming to run multiple computations simultaneously in real-time.

Experiments with six adult male American cockroaches were conducted to evaluate the optimization strategy. The test bed is made up of a circular arena with a diameter of 1 meter and a video camera mounted on top of the testbed was used to record the position and tracking the different cockroaches.

During each experiment, data was recorded about the movement of each cockroach using an *Inertial Measuring Unit* (IMU). Then, this data was used to train the machine learning classifiers offline before implementing them for online motion recognition and automatic stimulation.

The overall experimental scheme is shown in Fig. 2.5 where the relationship between the living organism and the instrumentation is highlighted.

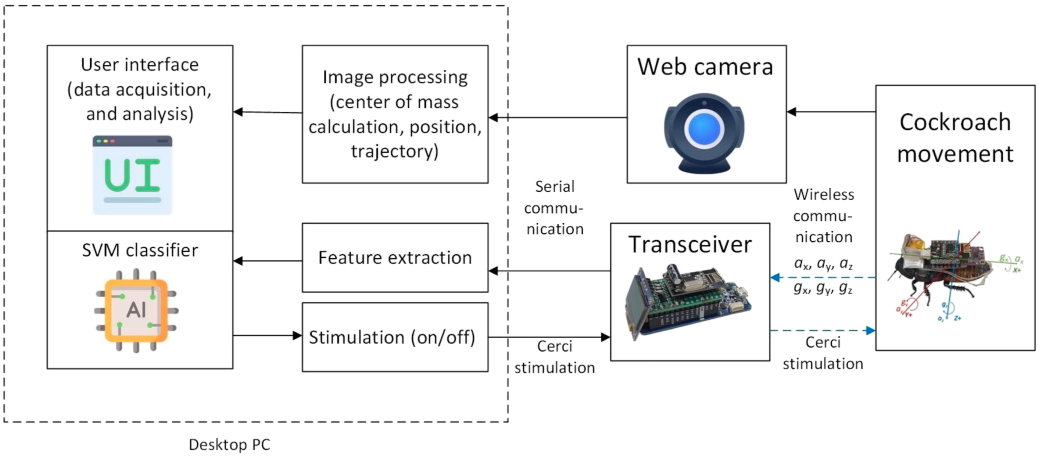

Fig. 2.5 Implemented machine learning on the online classification and stimulation feedback for the cockroach [4]

The results of this research showed that the optimization strategy was successful in increasing the search rate and distance traveled by cyborg cockroaches while reducing their stop time. The average search rate has increased by 68%, while the average distance traveled increased by a total of 70%. Finally the average stop time decreased by 78%.

2.3.2 Teleoperated Locomotion

This second research [3], aims to develop a teleoperation method for controlling biobots from a remote location with electrical stimulation. The study is divided into two sections, one with an obstacle and one without, to test the effectiveness of the teleoperation method in different scenarios. The experimental setup involves a teleoperated biobot testbed located in Osaka University, *Japan*, and an operator located in Chittagong, *Bangladesh*.

The biobot testbed consists of five biobots that are controlled by the operator using a remote laptop. The biobots are tasked with following a predetermined path, with an obstacle placed in the middle of the path in one section of the experiment and arrive to the finish line, which is also equipped with a cage gate that can be opened or closed.

The materials used in the current study include an electronic backpack, a remote laptop with a software platform, cockroaches with implanted electrodes interfaces, a

Table 2.2 Keyboard keys for controlling a CI remotely [3]

Keyboard Keys	Functions
Space Bar	Open or Close the cage gate
a	Stimulation on right antenna
s	Stimulation on left antenna
d	Stimulation on right cercus
f	Stimulation on left cercus
up	Stimulation on right and left cercus
left	Stimulation on right antenna
right	Stimulation on left antenna

camera to track the trajectory of the biobots and a cage with a teleoperated gate used as a target location. The biobot testbed consists of five cockroaches, each of which is equipped with the backpack and a set of electrodes implanted on their antennae, cerci, and thoraxes. The electrodes are made of platinum wire insulated with Teflon and have a diameter of 0.127 mm. The electronic backpack of the biobot is connected to the implanted electrodes using a pin header of 2.54 mm (female 5-pin single-row strip).

The operator controls the biobots using a set of keyboard keys, which are listed in Table 2.2. The keys allow the operator to stimulate the right and left antennae and cerci of the cockroach, which in turn controls the movement of the biobot. The cage gate of the testing environment can also be opened or closed using the teleoperated command.

The remote laptop is used by the operator to control the biobots using a set of keyboard keys. The user laptop, which can be located anywhere in the world with an internet connection (Chittagong, Bangladesh), is connected via *Virtual Network Computing* (VNC) to the testing PC in Osaka, Japan, which in turn is connected to the biobot testbed via a wireless radio connection. This setup allows the operator to send commands to the biobot and monitor its movements using a web camera displayed on the remote UI.

The software used in the current study is developed on top of the software already described in Chapter 2.2, with the added feature of communicating telematically with a computer on the other side of the world. The developed UI allows the operator to send stimulation commands to the implanted electrodes on the cockroach, which in turn controls the movement of the biobot. The program also allows the operator to open and close the cage gate of the testbed using a command on the keyboard.

The hardware piece (or backpack), is completely analogous to the one described in Chapter 2.2, with a Seeduino XIAO microcontroller base, with a wireless receiver to obtain the stimulation commands and an IMU sensor to measure the movements of the cockroach.

The cockroach used in the study is the Madagascar hissing cockroach (MHC). As explained in Chapter 5, The cockroaches were treated weekly by providing new food and cleaning the containers. For the anesthetization method needed to perform surgery, contrary to the previously described method, this time the cockroaches were placed in a container with small chunks of ice for around 30 minutes. Consequently, they were able to stay asleep for 10 to 15 minutes.

The electrodes were implanted on both antennae, both cerci, and the thorax of the cockroach (ground electrode). The cockroach antenna was cut about 5 mm from the tip, cerci were cut about 1 mm and a 3 mm deep hole was drilled in the thorax of the cockroach. The platinum electrode was inserted into the cut end of the antennae, cerci and ground hole. The cockroach was then allowed to recover for 24 hours before being used in the experiment.

The results are shown in Fig. 2.6, where some trajectories of the biobots are displayed. We can observe how the cockroaches were able to follow the predetermined path when stimulated by the user, initiating forward motion when stimulated on the cerci and turning motion when stimulated on the antennae, and how the teleoperation was successful in making the user able to control the biobot despite the long distance.

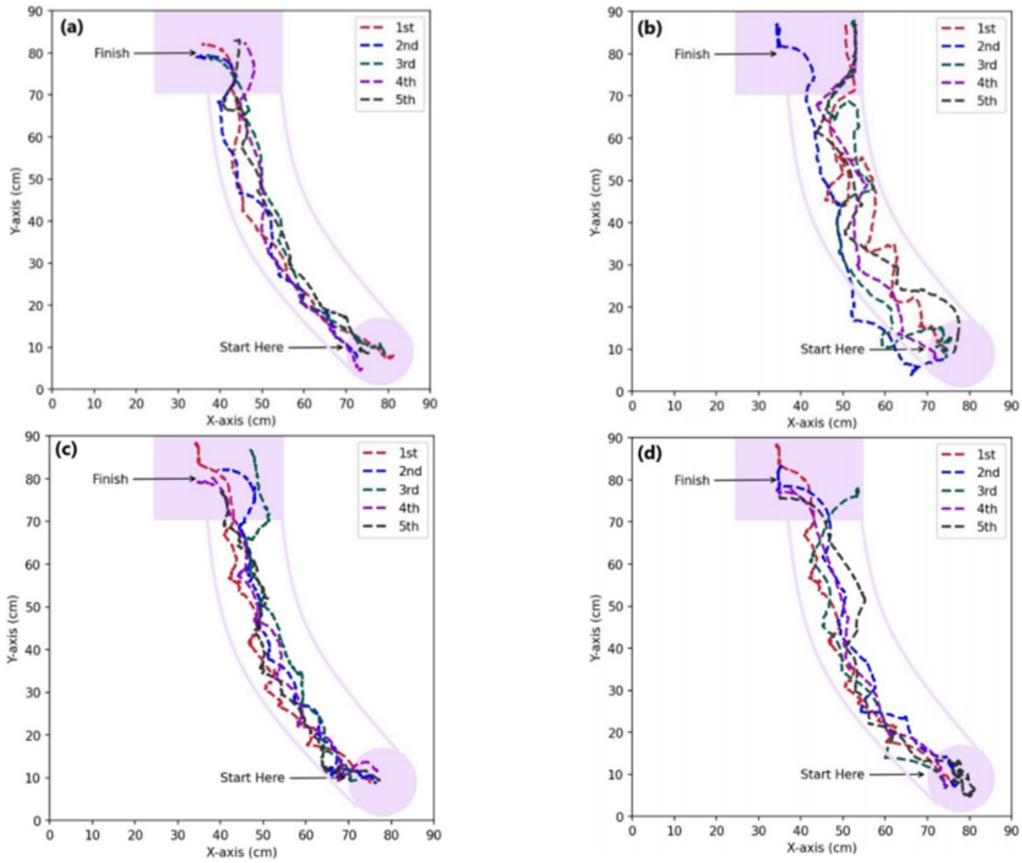

Fig. 2.6 Trajectories of teleoperated CIs from Bangladesh to Japan [3]

This particular research is significant because it explores a new method of controlling biobots that could have practical applications in various fields, such as search and rescue operations, where the biobot might have to be deployed in environments far away from the user, or too difficult to access.

2.4 Overview of Other Cyborg Insects

As already stated previously in the thesis, the cyborg cockroach developed at Morishima Lab is just one out of many different designs of CIs, with different animals used, different designs and different functionalities. In the following paper by P. T. Tran-Ngoc et al. [27], the main past and active CI projects are shown conveniently in table form, which is here reported in a modified version in Table 2.3.

Table 2.3 Chronological developement of insect-computer hybrid robots [27]

No.	Year	Authors	Insect	Locomotion control
1	1997	Holzer et al.	MHC	Left-Right turns
2	1998	Moore et al.	MHC	Left-Right turns, acceleration
3	2014	Latif et al.	MHC	Left-Right turns
4	2014	Whitmire et al.	MHC	Left-Right turns
5	2015	Sanchez et al.	PA*	Left-Right turns
6	2016	Cao et al.	MTU**	Walking, flying
7	2017	Dirafzoon et al.	MHC	Left-Right turns, acceleration
8	2017	Vo Doan et al.	ZM***	Left-Right Turns, Backward motion
9	2020	Nguyen et al.	ZM	Sideways acceleration
10	2020	Iyer et al.	ZM	Vision for cockroaches
11	2022	Songsong et al.	LM****	Jump
12	2022	Sriranjan et al.	MHC	Left-Right turns, acceleration
13	2022	Mochammad et al.	MHC	Left-Right turns, acceleration
14	2022	Yuga et al.	MHC	Left-Right turns, acceleration
15	2022	Nguyen et al.	ZM	Left-Right turns, acceleration
16	2022	Tran-Ngoc et al.	MHC	Left-Right turns, acceleration

* = *Periplaneta Americana*
** = *Mecynorrhina Torquata Ugandensis*
*** = *Zophobas Morio*
**** = *Locusta Migratoria*

As it is shown in Table 2.3, this variety of designs is explained by both the relative novelty of this research topic, that has not yet been able to produce a sufficiently efficient design that can be replicated by other teams, and also by the versatility of this technology and variety of possibilities in which it could be employed.

2.4.1 Cyborg Beetle

The research conducted in Nanyang Technological University, Singapore by Professor H. Sato [30], describes the design of a flying cyborg.

This CI is a micro aerial vehicle that uses a living beetle as its platform. It is a hybrid robot that combines the biological properties of the beetle with the technological capabilities of a wireless backpack controller. The goal of the cyborg beetle is to achieve flight control through electrical stimulation of the beetle's flight muscles, which allows it to mimic the flight maneuvers of real insects.

The cyborg beetle consists of two main components: a miniature wireless backpack and a base station connected to a computer. The backpack is mounted onto the beetle and is driven by a micro poly lithium ion battery. The backpack is customized using the *TI CC2431* microcontroller with a tiny I/O header for connecting the electrodes and a microbattery. The battery is wrapped with retro-reflective tape and mounted on the top of the backpack to supply power and serve as a marker for motion tracking.

The beetle's subalar muscles are located in the posterior part of the thorax, next to the basalar muscle. They run from the hind leg coxa to an apodema that connects to the subalar sclerite. The subalar muscle is responsible for controlling the beetle's wing stroke amplitude, which is essential for flight control. The beetle's elytra are removed to expose the subalar sclerite, which shows the connection to the wing base via a flexible membrane.

The cyborg beetle is controlled through electrical stimulation of the subalar muscles. The wireless backpack controller sends electrical signals to the electrodes attached to the subalar muscles, which causes them to contract and relax. By varying the frequency and amplitude of the electrical signals, the cyborg beetle can achieve different flight maneuvers, such as pitch, roll, and yaw. The base station connected to the computer receives data from the motion tracking system and sends commands to the wireless backpack controller.

The cyborg beetle is an exciting development in the field of micro aerial vehicles. It inherits all the capabilities and properties of the living insect while bypassing complex mechanical and material design as well as fabrication processes. The cyborg beetle has the potential to be used in various applications, such as search and rescue, environmental monitoring, and military surveillance, analogously to the Cyborg Cockroaches described in the other chapters. A picture of the flying cyborg beetle is shown in Fig. 2.7.

Fig. 2.7 Picture of a Flying Cyborg Beetle [30]

2.4.2 Cyborg Locust

In the research [17], the author describes the first attempts at designing a jumping cyborg starting from a live locust. This is in fact, a first attempt at creating a biohybrid jumping robot that combines the natural abilities of a locust with the control of an electronic system. The robot is made by transforming a live locust into a cyborg using exogenous electrical stimulations applied to two muscles of the locust's hind leg, the flexor muscle and the extensor muscle. The flexion and extension motions of the hindleg are well controlled accordingly, allowing the robot to jump with precision.

The cyborg locust retains its internal body-righting mechanism, which means the robot can quickly recover its posture for consecutive jumps. This work is a foundational step towards a fully controllable biohybrid jumping robot. The abilities of self-body righting and consecutive jumps are important for micro-jumping robots. After integrating the steering ability in the future, this cyborg jumping robot can be used in uneven surfaces or spaces with obstacles where the micro crawl-robot cannot pass through.

The cyborg locust is a promising technology for search and rescue in narrow spaces, concealed environments, or some confined environments. It can be used for human detection in narrow or covered spaces in a disaster area. Also, this cyborg locust is able to perform tasks in the wild on grass or leaves where crawling robots of the same size cannot step over.

The integration of these functions into a compact backpack is still a challenging task that awaits further advances in electronic technology. Nonetheless, the cyborg locust is a significant breakthrough in the field of microrobotics, and it opens up new possibilities for the development of biohybrid robots that can perform complex tasks in challenging environments. The picture of a Cyborg Locust is shown in Fig. 2.8.

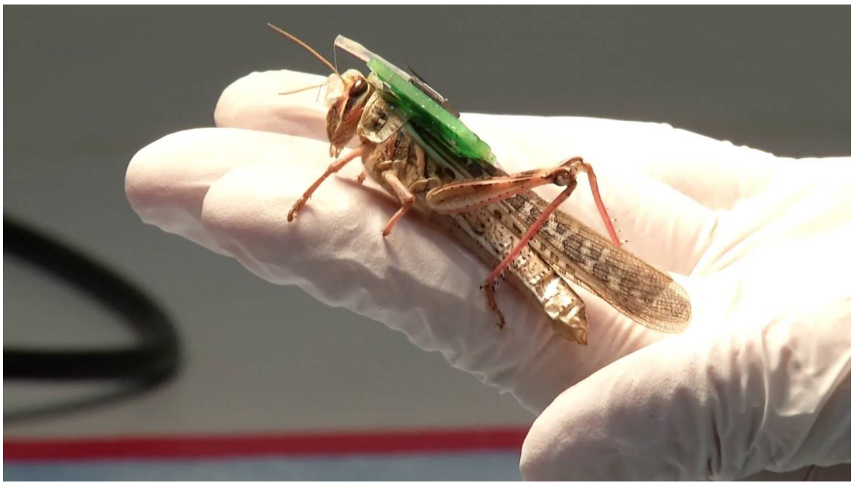

Fig. 2.8 Picture of a Cyborg Locust [6]

Chapter 3

Electrical Stimulation Theory

It is useful to understand the theory behind neural and muscle electrical stimulation before analyzing experiments performed on CIs. As it was already explained in previous Chapters, the MHC can respond to different types of stimuli (electric, vibrational, chemical ecc.) [11] and react accordingly. This section will briefly present the historical background related to the discovery of how electrical discharges can be used to stimulate muscle movements in virtually all organisms.

The medical use of electrical currents has been known for more than 2000 years, as there are records of how both Romans and Ancient Egyptians used electric shocks from different species of fish to treat headaches or gout [23].

Using a bimetallic rod, Luigi Galvani demonstrated the electrical activation of nerves and muscles in 1791. He believed that the discharge of "animal electricity" was what caused muscles to contract, but in 1793, Volta discovered that the bimetallic rod was the genuine source of electricity, not the animal. Without knowing the behavior of the membrane that surrounds the nerve fiber, it is impossible to comprehend what actually occurs when a nerve is electrically activated. As a result, numerous competing hypotheses developed over the years until the publication of the well-known study by Hodgkin and Huxley. They used voltage clamp experiments to conduct current-voltage analyses on the giant squid axons, which led them to the discovery of the mechanism underlying the excitability of nerve fibers in 1952 [23].

The 'Leyden jar' by Muschenbroeck, created in 1745, gave electrotherapy a wide range of uses. Many researchers looked at relationships between signal strength and stimulus duration that could match the duration of the experiment. A formula for the voltage V required to produce an excitation was published in 1892; it is shown in (3.1).

$$V = a * R + \frac{b}{C} \tag{3.1}$$

where V is the voltage to which the capacitor (the Leyden jar) is to be loaded, R is the resistance of the discharge unit, C is the capacity, and a and b are coefficients determined by the specimen [23]. The following threshold relations, where the charge Q, voltage V, or current I were expressed as functions of duration , were found by other early investigators

$$\begin{aligned} Q &= a + b\tau \\ V &= \frac{a}{1 - e^{-\frac{\tau}{b}}} \\ I &= \frac{a}{\sqrt{\tau}} \end{aligned} \tag{3.2}$$

All these formulas in (3.2) show that the stimulus signal strength decreases with increasing pulse time. These formulations, taken from [23], demonstrate that even for an infinite application, the signal amplitude does not lie below a certain value, which is in accordance with modern data about muscle stimulation.

Functional electrical stimulation requires some fundamental understanding of the process of natural excitation in order to be applied scientifically. We now understand that the nervous system transmits information by means of Action Potentials (AP), which travel along nerve fibers (axons). The theory that impulse propagation results from current flow from an active region that stimulates the resting region ahead was developed. According to the *All-Or-None Concept*, the propagating AP has a specific strength and cannot travel great distances if it is too weak [23].

Experiments on the axons of giant squids made advancements in our understanding of the transmission of nerve signals possible. This was made possible by the extremely large axon diameter, up to 1 mm, which allowed the insertion of microelectrodes at the time. The Hodgkin-Huxley equations, a set of four differential equations that describe membrane behavior, provided a breakthrough in understanding the propagation process without having a clear understanding of membrane kinetics [23].

The types and quantity of ionic channels play a major role in determining the characteristics of a biological membrane. Naturally, there are differences in quality between the membranes of living cells. In the Nodes Of Ranvier, where the membrane is covered with multiple sheets of insulating myelin, the myelinated axons of vertebrates have regions with high activity, whereas there is very little current flowing across the membrane in the internodal region. Technical progress allowed the measurement of myelinated frog axons, which have diameters of some μm only [23].

The voltage-current relations of a piece of membrane are quantitatively described by the Hodgkin-Huxley equations and their modified form, as well as the Frankenhaeuser-Huxley equations [23]. An electrical circuit made up of a voltage source, a capacity, and nonlinear resistance can mimic the behavior of such a membrane patch (Fig. 3.1). If we assume an inside potential V_i and an external potential V_e, we obtain the voltage $V = V_i - V_e$ across the membrane. The current Im through the membrane will be calculated with (3.3).

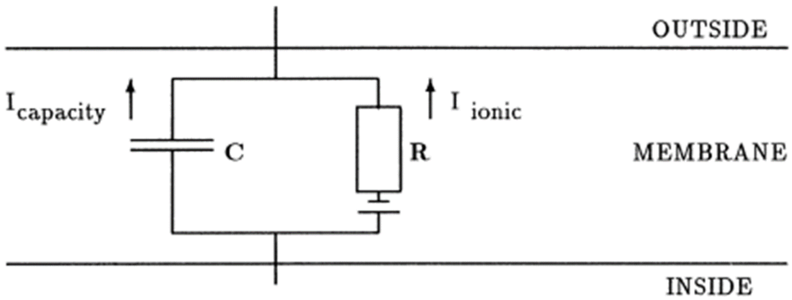

Fig. 3.1 Model of a membrane patch as an Electric Circuit [23]

$$I_m = I_{capacity} + I_{ionic} = C * \frac{dV}{dt} + \frac{V}{R} \tag{3.3}$$

where C is the capacity of the membrane and R (which is a function of V and time t) is the nonlinear membrane resistance. This is one differential equation; the remaining three differential equations developed by Hodgkin and Huxley are utilized to statistically explain the gating (opening and closing) of membrane channels. Only because the membrane's conductance to ionic currents is mostly voltage-dependent is the entire process of nerve signal propagation conceivable.

These studies helped arrive at a theoretically and practically feasible explanation for animal or human stimulation of muscle through electricity.

A nerve or muscle fiber's interior is often kept at a potential that is between 50 and 70 mV negative to the exterior due to differing ionic concentrations at the interior and exterior of the fiber. The voltage changes to positive values when an action potential is generated before returning to its initial resting condition. Such an action potential spreads since it disturbs the resting region in front on its own and causes channel activity there as well. By artificially increasing the inner potential with the aid of an inserted microelectrode, a similar effect can be achieved. However, for therapeutic applications, inserting an electrode into the cell is typically impractical; therefore, extracellular potential is typically used to modify membrane voltage in order to excite nerve and muscle fibers.

3.1 Issues with Electrical Stimulation

Despite the fact that electrical stimulation is the most popular approach for communicating with cockroaches due to its low power consumption and simplicity in design, electrical stimulation of living organisms has drawbacks as well. The first is that invasive surgery on a living organism is required in order to stimulate the nervous system. This suggests that the cockroach will experience some level of stress, depending on the anesthesia technique and the kind of operation that needs to be done. As demonstrated in earlier study, CO2 can impair an animal's responsiveness to stimuli [9]. Additionally, the exoskeleton's muscular and neurological tissues can deteriorate as a result of the electrical shocks that occur inside the cerci and antennae, which can also hasten the corrosion of the electrodes [24]. This is the underlying reason of the habituation to stimulations problem, which is undoubtedly one of the most important to overcome, since losing control of a bio-bot because it stops responding to stimuli can quickly result in the failure of a rescue mission.

3.2 Biphasic vs Monophasic Signals

Electrical waveforms can be classified in two macrogroups, namely monophasic and biphasic These two different types of waves are frequently employed in medical applications, particularly in the areas of defibrillation and neural stimulation. The direction of current flow is the main distinction between the two. A monophasic waveform has a single phase, with each pulse's electrical current flowing solely in one direction. A biphasic waveform, on the other hand, consists of two phases, each having an opposing current flow direction. A positive current may be present during the first phase, followed by a negative current during the second phase, or the other way around. Biphasic waveforms have been proven to be more efficient in defibrillation because they can give a higher overall amount of energy at a lower peak voltage, minimizing the risk of injury or damage to the heart tissue [21]. Additionally, biphasic waveforms have been demonstrated to be better suited for muscle stimulation because they greatly reduce electrode corrosion and harm to the stimulated tissues [24][19].

Chapter 4

Study of Electrical Stimulation on the Cyborg Insects

In this Chapter, the first part of the experimental section of my thesis project will be described. This first section will try to precisely map the relationship between the parameters of the input signals given to the cockroach (Voltage, Frequency, Type of wave) and determine which parameters or combination of them gives the best output in terms of accuracy and repeatability of the experiments. It is important to note that the current stimulation method used in the CIs used in *LiveMechX* lab is a square monophasic waveform with frequency equal to 50Hz and Voltage equal to 3.3V [3].

4.1 Experimental Setup Description

This section will deal with the description of all the materials needed for the performed experiments, including a remark on the biological frame used, the different and unique type of surgery used for these experiments and the hardware piece and software useful for the retrieval and manipulation of the data.

4.1.1 Cyborg Insect

The CI platform, the MHC, was selected due to its size range of 5 cm to 7 cm when completely developed. Fresh food and container cleaning were provided on a weekly basis for the cockroaches. The study strictly adhered to ethical standards. The cockroaches were put in a container and anesthetized with CO_2 gas for about 1 to 2 minutes. They then fell asleep for about 5 minutes and then went into an analgesic semi-sleep for another 15 to 30 minutes. The electrodes were platinum wires that were inserted on the abdomen and whose Teflon shielding was melted away using a lighter.

The two wires that provided the input stimulation and the implanted electrodes were connected by a female pin header (2.54 mm, 4-pin single-row strip) that was glued to the thorax. On the abdomen, close to one of the cerci, a tiny hole was cut with a surgical drill (approximately 1 mm from the rear and 2 mm from the side), and a platinum electrode was inserted about 3 mm deep and fastened with adhesive. The cercus' platinum electrode was attached to the pin header by a copper wire. About 3 mm of the upper abdomen's midline were used to introduce the ground electrode, which was then soldered to the pin header using another copper wire. The cockroaches were given a day to recover and rest in a container following the operation [11].

4.1.2 Hardware

The JDS6600 DDS signal generator was utilized to produce the various signals investigated in this study. It is a 2-channel waveform generator that can produce a variety of waveforms. Additionally, unique waves can be created using the computer programme created by the same business, JOI-IT. Voltage and frequency changes can be made to control the waveforms. Since only one cercus was electrically stimulated at a time, only one channel was employed for the studies.

Two lengthy copper wires (1.6m) were attached to both the negative and positive ends of a "BNC Male to Dual Banana Male Connector" that was used to split the output signal from the generator. The wires were soldered to a set of 2-pin single row strip male pin headers at the opposite end. Following that, the latter is attached to the female header that is permanently adhered to the MHC's thorax. The Bio-bots were put to the test in a square 88x88cm arena. A "Logitech C922 Pro Stream" webcam that can record HD 1800p video of the cockroach's movements is mounted on the roof of the arena [11].

4.1.3 Software Used for Data Processing

The software Kinovea was used to process the videos of the CIs by monitoring their movement patterns immediately after being stimulated. The trajectories were plotted using a Python program that could normalize their starting position to the center of the arena after being saved as a *.csv* file [11].

4.2 Testing and Preliminary Results

All tests were performed once on two different cockroaches to avoid biases (A and B). For the first set of experiments, we compared the response of the cockroaches to stimulation with a Biphasic Square Wave (B1), changing the Voltage first and the Frequency after, in order to check the difference that the changing parameters have on the accuracy of the cockroach response. In the second section of the experimentation, we explored the claim that different types of biphasic waveforms can have better performance when it comes to habituation to stimuli [14].

4.2.1 Accuracy When Varying Voltage and Frequency

Table 4.1 and Figure 4.1 show the results obtained testing the Accuracy of the trajectories of the cockroach when given electrical stimulations at different voltages. We measured the percentage of acceptable output trajectories for each cockroach and recorded their profile. An acceptable trajectory in the case of cerci stimulation looks like a forward motion slightly turned in the opposite direction to the stimulated cercus. Likewise, Table 4.2 and Fig 4.2 show the same acceptable trajectory percentage measured changing the Frequency of the electric wave.

Table 4.1 Accuracy, changing the voltage (50Hz,B1)

Voltage	Acceptable/Total Stimulations		Accuracy	
	A	B	A	B
1.5V	3/30	2/30	10.0%	6.7%
2.0V	9/30	3/30	30.0%	10.0%
3.0V	25/30	23/30	83.3%	76.7%
3.5V	27/30	26/30	**90.0%**	**86.7%**
4.0V	26/30	26/30	86.7%	**86.7%**

Table 4.2 Accuracy, changing the frequency (3V,B1)

Frequency	Acceptable/Total Stimulations		Accuracy	
	A	B	A	B
30Hz	8/30	4/30	26.7%	13.3%
50Hz	25/30	23/30	**83.0%**	**76.7%**
100Hz	14/30	18/30	46.7%	60.0%
150Hz	7/30	2/30	23.3%	6.7%
200Hz	4/30	3/30	13.3%	10.0%

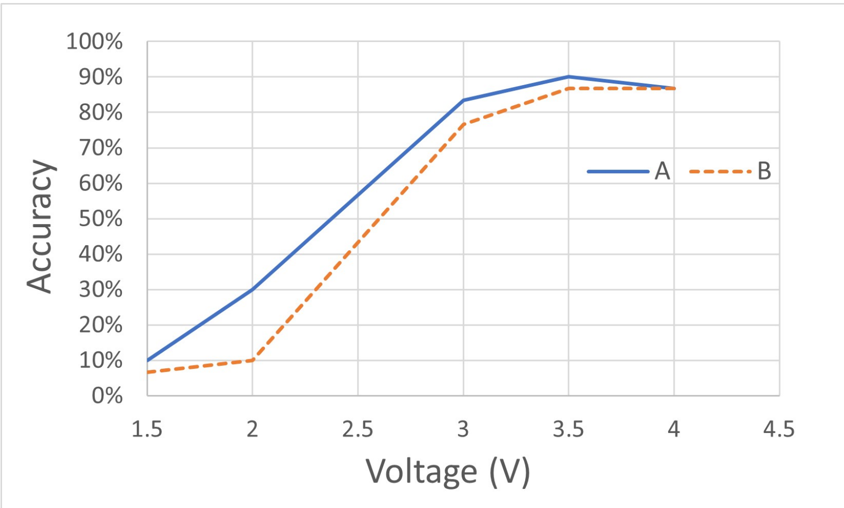

Fig. 4.1 Relationship between Voltage and Accuracy (A: Solid line, B: Dashed line) [11]

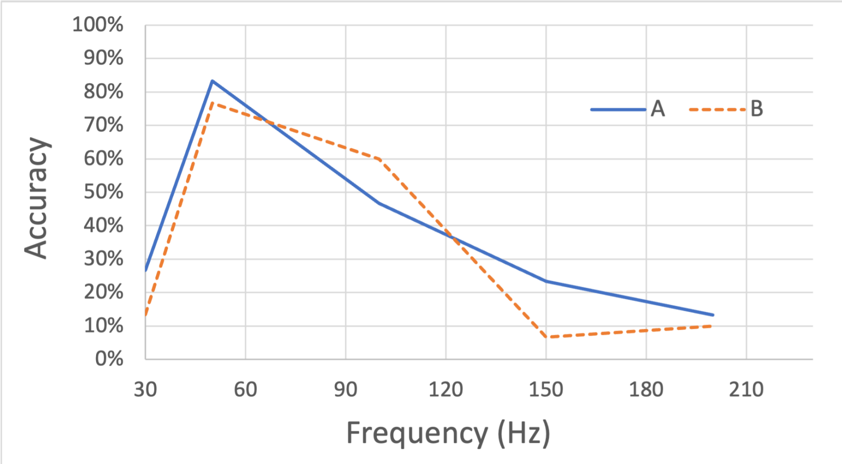

Fig. 4.2 Relationship between Frequency and Accuracy (A: Solid line, B: Dashed line) [11]

4.2.2 Accuracy When Varying Waveform

The experiments performed in this section are comparable to the previous ones. We used 4 different biphasic waveforms. This choice was taken according to previous research that has also used them to test the feasibility of biphasic signals [5]. The biphasic waves that we used are:

- (B2) Charge balanced with a fast reversal wave.
- (B3) Trapezoidal wave.
- (B4) Asymmetric square wave, with an amplitude from H to -2H.
- (B5) Triangular wave.

while the data regarding stimulation with a square monophasic wave, 3.3V, 50Hz (M1) is taken from past research [20]. The waveforms' profiles that were studied are shown in Fig. 4.3. The tests were conducted on 2 cockroaches and the data is summarized in Table 4.3 and Fig. 4.2. For the test with waveform B2, the stimuli were divided into 2 sets: one where the cockroaches were stationary at the start, and one where they were already moving. To better show the expected trajectory that the cockroaches should follow, we plotted some of the responses obtained with the different waveforms in Fig. 4.5.

Table 4.3 Accuracy, changing the waveform (3V,50Hz)

Waveform	Acceptable/Total Stimulations		Accuracy	
	A	B	A	B
B1.	25/30	23/30	**83.3%**	**76.6%**
B2.	11/30	12/15	36.7%	40.0%
B2(Non-stationary).	11/15	10/15	73.3%	66.7%
B3.	11/30	13/30	36.7%	43.3%
B4.	18/30	20/30	60.0%	66.7%
B5.	8/30	6/30	26.7%	20.0%
M1. [3]	39/40		**95.0%**	

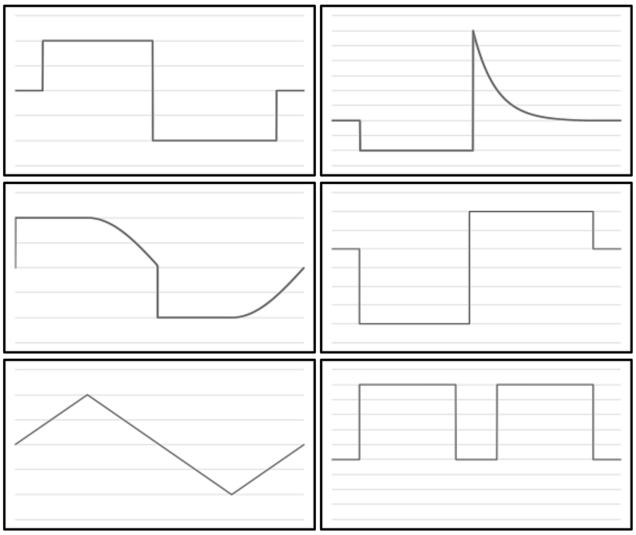

Fig. 4.3 From left to right and top to bottom: (B1) square biphasic, (B2) charge balanced, fast reversal, (B3) trapezoidal, (B4) charge unbalanced, (B5) triangular, (M1) square monophasic. [11]

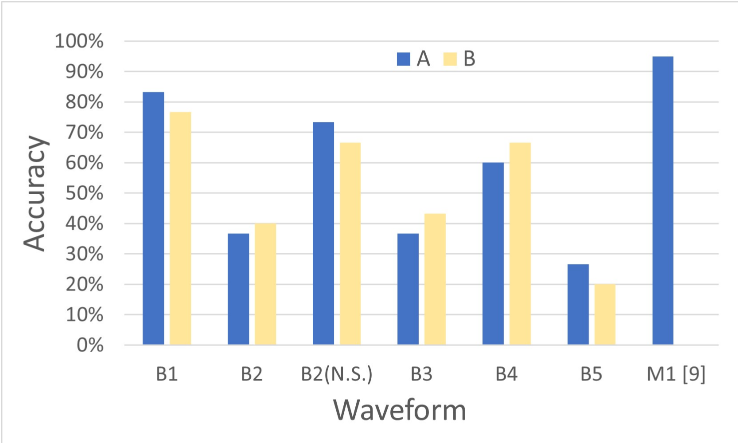

Fig. 4.4 Relationship between Waveform and Accuracy, (A: Left bar, B: Right bar) [11]

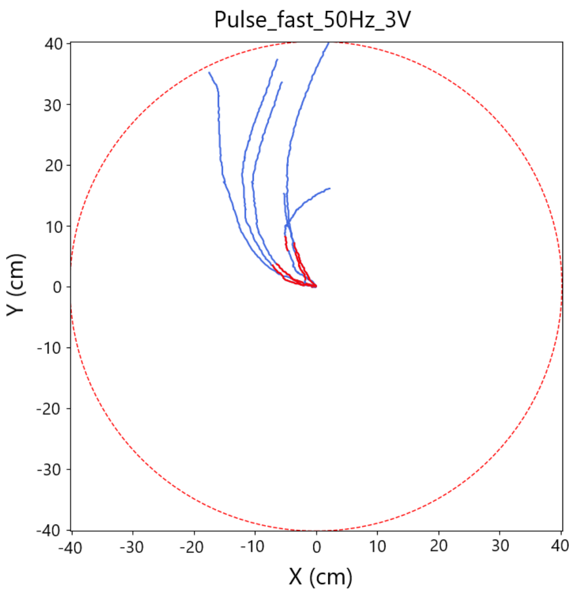

Fig. 4.5 Some acceptable trajectories of the cockroach with B2 stimulations (left cercus stimulated). [11]

4.2.3 Preliminary Results

The experimental data for the first tests clearly shows direct proportionality between the stimulation voltage and the repeatability of tests, with a maximum accuracy ratio of 90.0% for a biphasic pulse wave at 3.5V.

It is important to note that with a stimulation of more than 4V, the cockroaches started to look visibly uncomfortable to the stimulations, with arching of their abdomen and fast unnatural movements. Concerning the tests changing the frequency of stimulation, we observed that the cockroaches responded best to stimulations of 50Hz frequency, with a decrease in accuracy both to lower and higher frequencies.

In the second experiment set, the data shows that square waves (both monophasic and biphasic) are the most efficient in assuring good repeatability of outcomes, with an accuracy ratio that goes above 80% for the monophasic one.

As shown for B2, the cockroaches tended to show significantly better output trajectories when they were stimulated while already in motion. This phenomenon was also registered with the other biphasic signals, but at a slightly lower rate. From this fact we can theorize that biphasic waves are more efficient in making the CI steer, rather than making it initiate forward movement. The cockroaches stimulated with biphasic waves did not show signs of habituation during the total duration of the experiments, even if stimulated for up to 150 times in a day.

Some problems that may have contributed to some low accuracy percentages could be related to the dissipation of energy given by the length of the wires connected to the signal generator, as well as some problems with the electrode surgery in the nervous system of the cockroach.

This may also explain the better results that were obtained with M1 in the previous research [20], since those tests were performed with a backpack mounted on top of the thorax of the insect, with limited dissipation.

Chapter 5

Experimental Modelling of the Cockroach

The physiology of MHCs allows us to consider each cockroach as a hybrid mobile robot which is acted upon through four input voltages, two applied to the antennae and two to the cerci, Fig. 5.1. The MHC is a system with four inputs.

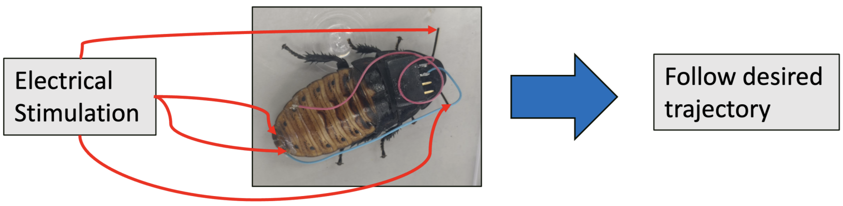

Fig. 5.1 Schematic representation of the MHC system

In the remainder of the thesis, it will be adopted the notation, which identifies respectively with the subscript *RC* what is obtained by applying a stimulation to the *Right Cercus* (input voltage V_{RC}), with the subscript *LC* what is obtained by applying a stimulation to the *Left Cercus* stimulation (input voltage V_{LC}), with the subscript *RA* as that obtained by applying stimulation to the *Right Antenna* (input voltage V_{RA}), and with the subscript *LA* as that obtained by applying the *Left Antenna* a stimulation (input voltage V_{LA}).

5.1 Kinematic Model of the Cockroach

The kinematic equations of the MHC regarded as a hybrid mobile robot can be expressed as follows in (5.1).

$$\begin{aligned} \dot{x} &= cos(\theta)v, \\ \dot{y} &= sin(\theta)v, \\ \dot{\theta} &= \omega \end{aligned} \tag{5.1}$$

where x is the global x-position of the MHC, y is the global y-position of the MHC, θ is the global heading of the MHC, v is the linear velocity of the MHC, and θ is the angular velocity of the MHC. The state variables of the hybrid mobile robot are x, y, and θ. The linear and angular velocities, respectively v and θ, are nonlinear functions of the four input voltages and can be expressed as follows $v = f(V_{RC}, V_{LC}, V_{RA}, V_{LA})$ and $\theta = g(V_{RC}, V_{LC}, V_{RA}, V_{LA})$.

The above equation (5.1) is analogous to the equation which describes the movement of a unicycle robot on a plane [15]. A unicycle robot model on a plane refers to a simplified representation of a robotic system that moves similarly to a unicycle, with a single wheel allowing it to traverse a flat surface. This model is characterized by its ability to move forward or backward along a straight path, as well as turn to change its direction. Two primary variables define its position on the plane: its coordinates (x, y) denoting its location and an angle θ indicating its orientation or direction of travel. Control inputs typically include linear velocity (related to how fast it moves forward or backward) and angular velocity (indicating the speed of turning or changing direction). The unicycle robot model is often used in robotics research due to its simplicity, serving as a foundational platform to study control strategies, motion planning, and navigation algorithms in two-dimensional spaces. [15]

The next step necessary to obtain the MHC-specific kinematic model (5.1) was to understand through experiments how the input voltages influence the state variables, that is to find the nonlinear functions $f(V_{RC}, V_{LC}, V_{RA}, V_{LA})$ and $g(V_{RC}, V_{LC}, V_{RA}, V_{LA})$. The procedure followed is described in section 5.

5.1.1 Experiments to Find a Model

Several experiments were performed exploiting the previously described experimental setup. The tests carried out aimed at collecting data to allow to find a mathematical model expressing the relationship between the input voltages applied and the output linear and angular velocity of the MHC.

Experimental Setup

The experimental setup used to carry out the experiments is briefly described below. The procedure for surgery only differs from that described in section 4.1.1 because an additional step to connect the antenna was performed. Consequently, the surgery procedure will be here described again.

The cockroaches were put in a container and anaesthetized with CO_2 gas for about 1 to 2 minutes. They then fell asleep for about 5 minutes and then went into an analgesic semi-sleep for another 15 to 30 minutes. The electrodes were platinum wires that were inserted on the abdomen and whose Teflon coating was removed using a lighter. The two wires that provided the input stimulation and the implanted electrodes were connected by a female pin header (2.54 mm, 4-pin single-row strip) that was adhered to the thorax. On the abdomen, close to one of the cerci, a tiny hole was made with a surgical drill (about 1 mm from the back and 2 mm from the side), and a platinum electrode was inserted about 3 mm deep and fastened with glue, [11]. The cercus' platinum electrode was connected to the pin header by a copper wire.

Likewise, roughly 2 cm were cut from the right antenna and another platinum electrode was inserted 2cm deep inside the antenna and fastened with superglue; this electrode was connected with a copper wire to the pin header on the torax [11].

About 3 mm of the upper abdomen's midline were used to insert the ground electrode, [11], which was then soldered to the pin header using another copper wire. The locations of the electrodes on the abdomen and close to the cercus are shown in Fig. 1. The cockroaches were given a day to recover and rest in the container following the operation, [11].

The Hardware and Software are the same used for the experiments about the optimal voltage and waveform performed in the previous Chapter. For their description, refer to section 4.1.2 and 4.1.3.

Table 5.1 Experimental Data, RC and RA stimulation

Voltage V	Linear velocity RC $10^{-3} m/s$	Angular velocity RC $10^{-3} rad/s$	Linear velocity RA $10^{-3} m/s$	Angular velocity RA rad/s
1	0	0	0	0.78
1.2	0	0	0	0.80
1.4	4.4	0	0	1.02
1.5	8.6	10.3	0	1.02
1.8	15.6	50.4	0	1.45
2	25.7	168.4	0	1.55
2.5	48.9	102.8	0	1.68
2.7	20.4	114.7	0	1.42
2.9	32.4	76.3	0	1.54
3	51.9	99.6	0	1.50
3.3	39.8	81.2	0	1.95
3.5	78.8	47.5	0	1.31

Performed tests

In the experiments the CI was stimulated by applying different input voltages either on the cerci or on the antennae and the corresponding linear and angular velocities of the MHC were measured. Table 5.1 collects all the data obtained with different values of RC and RA stimulation.

The Curve Fitter app of MATLAB was used to find the best fitting curves to the data of the tests. Fig. 5.2 and Fig. 5.3 show the data-points and best-fit curves from the experiments measuring respectively the linear velocity and angular velocity with RC stimulation. Finally, Fig. 5.4 presents the experimental data-points and best-fit curve for the angular velocity with RA stimulation. The experiments showed that the linear velocity measured with RA stimulation is practically zero (see Table 5.1), since antenna stimulation almost causes the MHC to stop and only affects its orientation.

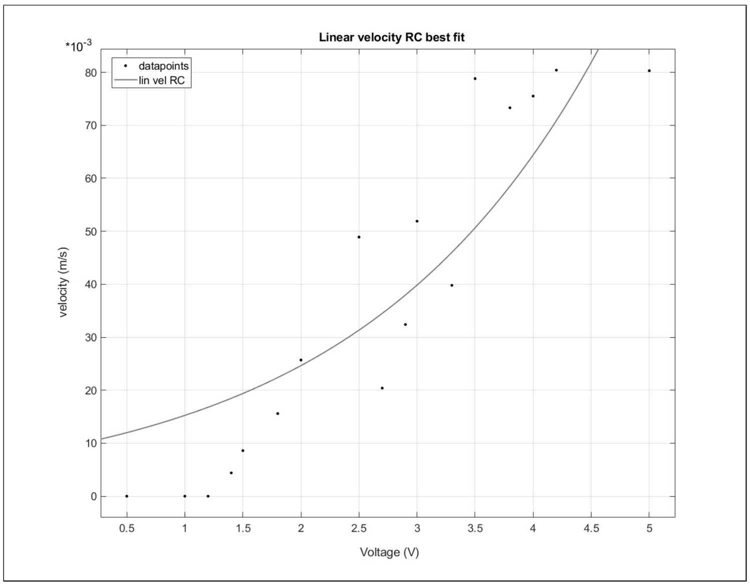

Fig. 5.2 Experimental data-points and best-fit curve of the linear velocity as the value of V_{RC} varies.

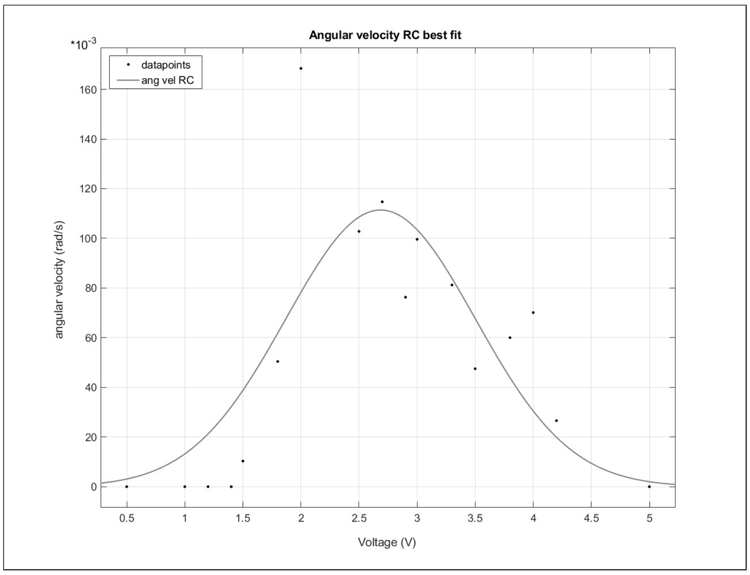

Fig. 5.3 Experimental data-points and best-fit curve of the angular velocity as the value of V_{RC} varies.

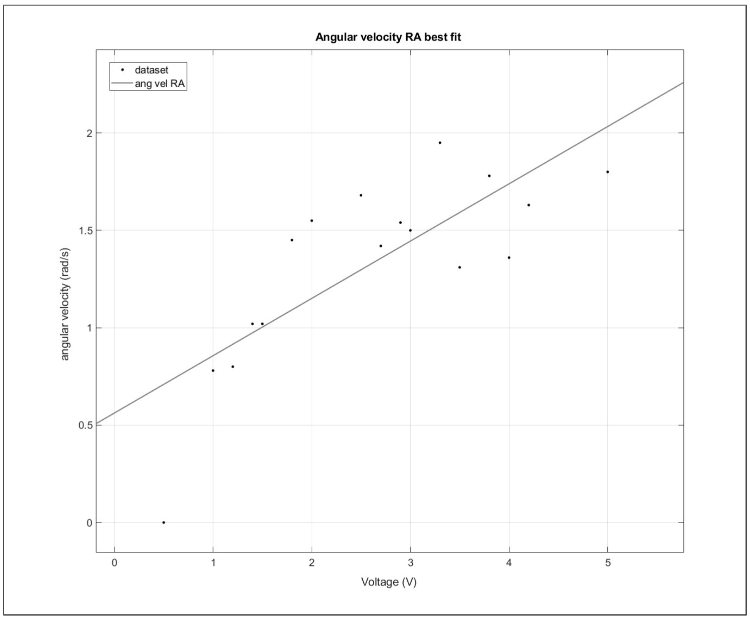

Fig. 5.4 Experimental data-points and best-fit curve of the angular velocity as the value of V_{RA} varies.

5.1.2 Experimental Equations

The kinematic model (5.1) MHC-specific when only the RC stimulation is applied turns out to be:

$$\begin{aligned} \dot{x} &= cos(\theta)k_1 e^{k_2 V_{RC}}, \\ \dot{y} &= sin(\theta)k_1 e^{k_2 V_{RC}}, \\ \dot{\theta} &= k_3 e^{-\frac{(V_{RC}-k_4)^2}{k_5^2}}, \end{aligned} \tag{5.2}$$

while when only the RA stimulation is activated it is obtained:

$$\begin{aligned} \dot{x} &= 0, \\ \dot{y} &= 0, \\ \dot{\theta} &= k_6 V_{RA} + k_7, \end{aligned} \tag{5.3}$$

where the values obtained for the constants k_1 to k_7 in (5.2) and (5.3) are reported in Table 5.2.

Table 5.2 Model Constants

Constants' symbol	Numerical value
k_1	0.0095
k_2	0.4797
k_3	0.1114
k_4	2.6851
k_5	1.1534
k_6	0.2942
k_7	0.5621

Experiments confirmed that the stimulation of an antenna at a time does not cause any forward motion, yet only a rotation opposite to the stimulated antenna (to the right when acting on the left antenna and vice versa), [12], [24]. Furthermore, the tests confirmed that the stimulation of a cercus at a time produces a forward motion and a slight rotation opposite to the stimulated cercus (to the right when acting on the left cercus and vice versa), [12], [24].

The experiments showed that the effect of stimulating one of the two cerci at a time (RC or LC) is the same with regards to linear velocity. Therefore the graph relating to linear velocity with LC stimulation is the same as the corresponding graph for RC (Fig. 5.2).

On the other hand, tests showed that by stimulating either only one of the two cerci at a time (RC or LC) or only one of the two antennae at a time (RA or LA) the effect is opposite as regards angular velocity. The angular velocity graphs given LC and LA stimulation are mirrored with respect to the x-axis respectively of the angular velocity graphs for RC stimulation (Fig. 5.3) and RA stimulation (Fig. 5.4).

In the light of previous considerations, the kinematic model (5.1) MHC-specific given only LC stimulation is expressed by:

$$\begin{aligned} \dot{x} &= cos(\theta) k_1 e^{k_2 V_{LC}}, \\ \dot{y} &= sin(\theta) k_1 e^{k_2 V_{LC}}, \\ \dot{\theta} &= -k_3 e^{-\frac{(V_{LC}-k_4)^2}{k_5^2}}, \end{aligned} \tag{5.4}$$

while with only LA stimulation it is obtained:

$$\begin{aligned} \dot{x} &= 0, \\ \dot{y} &= 0, \\ \dot{\theta} &= -k_6 V_{LA} - k_7, \end{aligned} \tag{5.5}$$

where the values of the constants $k_1 - k_7$ in (5.4) and (5.5) are reported in Table 5.2 and are the same as in equations (5.2) and (5.3).

MHC locomotion is described by the four nonlinear equations (5.2)-(5.5) each one corresponding to applying only one of the four input voltages at a time. The experiments confirmed that, although the CI is a nonlinear system, the effects due to each input voltage add linearly when the four input voltages are applied simultaneously. These results are in agreement with previous research, [22], which showed that the simultaneous stimulation of both antennae produces no effect on the cockroach (no forward motion and no rotation), and the simultaneous stimulation of both cerci achieves forward motion without angular displacement. Therefore the complete kinematic model MHC-specific is given by

$$\begin{aligned} \dot{x} &= cos(\theta) f(V_{RC}, V_{LC}, V_{RA}, V_{LA}), \\ \dot{y} &= sin(\theta) f(V_{RC}, V_{LC}, V_{RA}, V_{LA}), \\ \dot{\theta} &= g(V_{RC}, V_{LC}, V_{RA}, V_{LA}), \end{aligned} \tag{5.6}$$

where

$$v = f(V_{RC}, V_{LC}, V_{RA}, V_{LA}) = k_1 \left[e^{k_2 V_{RC}} + e^{k_2 V_{LC}} \right],$$

$$\omega = g(V_{RC}, V_{LC}, V_{RA}, V_{LA}) = k_3 \left[e^{-\frac{(V_{RC}-k_4)^2}{k_5^2}} - e^{-\frac{(V_{LC}-k_4)^2}{k_5^2}} \right] + k_6 (V_{RA} - V_{LA})$$

5.1.3 MHC ideal locomotion behavior

In order to show the MHC ideal behaviour under the application of an (open-loop) sequence of commands, a simulation over a time interval of 100s was performed. The MHC ideal locomotion is considered since no uncertainties and disturbances affecting the CI are taken into consideration. The applied sequence of 5 commands is the following:

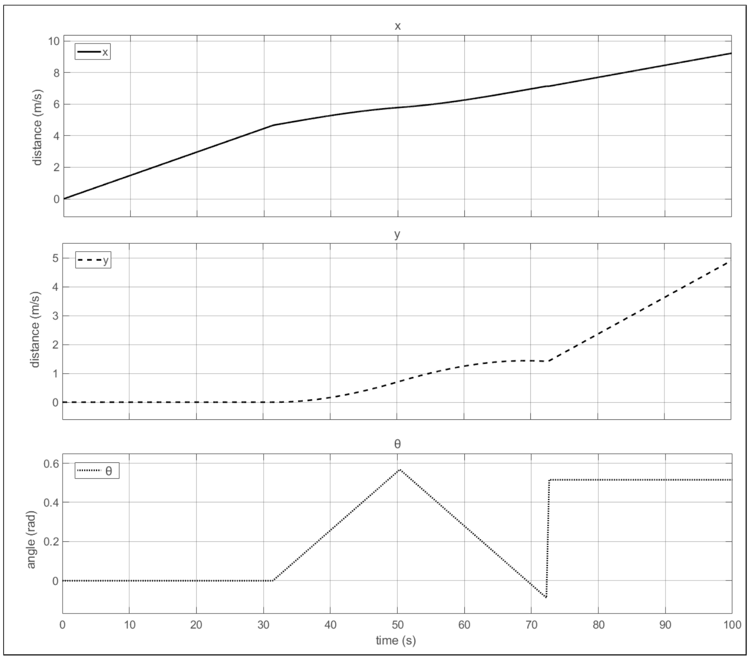

Fig. 5.5 State variables over the 100s time interval given the sequence of 5 commands: (1:RC+LC; 2:RC; 3:LC; 4:RA; 5:RC+LC).

1. RC and LC simultaneous stimulation for 31.9s, (RC+LC),
2. RC stimulation for 18.3s, (RC),
3. LC stimulation of 21.8s (LC),
4. RA stimulation of 0.7s (RA),
5. RC and LC simultaneous stimulation for 27.3s, (RC+LC).

Fig. 5.5 describes the evolution of the state variables over the 100s of the simulation. The trajectory is shown in Fig. 5.6, with the MHC starting point is at the origin of the $x-y$ plane.

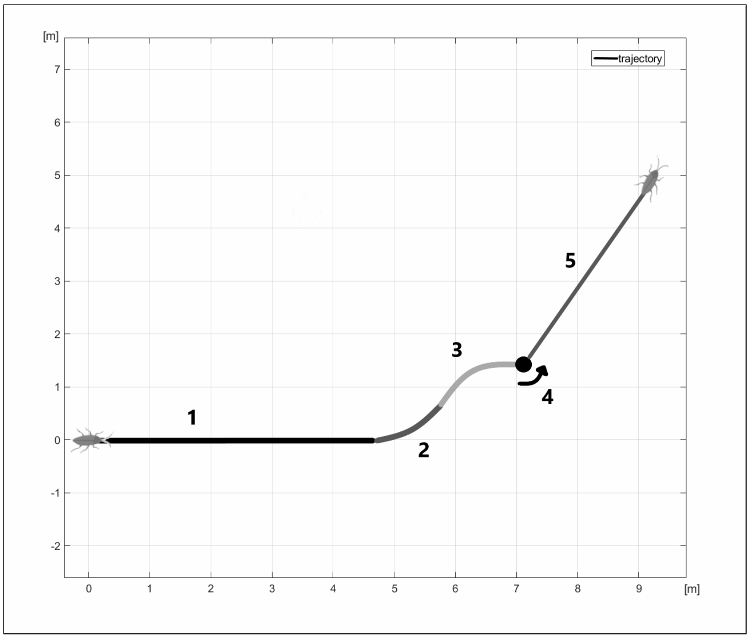

Fig. 5.6 MHC trajectory over the 100s time interval given the sequence of 5 commands: (1:RC+LC; 2:RC; 3:LC; 4:RA; 5:RC+LC).

Chapter 6

Sliding Mode Control for Cyborg Cockroach

6.1 Introduction to Sliding Mode Control

Sliding Mode Control (SMC) stands out as a powerful tool in the vast sector of control engineering. The SMC fits into the broader field of Variable Structure Control (VSC) and exhibits important features of robustness against uncertainties and disturbances that have established its reputation among researchers and practitioners. In order to delve deeper into SMC, it is essential to understand its setting in the context of Nonlinear Control and particularly Variable Structure Control.

Nonlinear control comes from the knowledge that many systems exhibit less-than-linear behavior under the operating conditions of interest. Many systems, both natural and engineered, exhibit nonlinear characteristics that defy the simplifications provided by linear models. Nonlinear behavior can be due to several factors and modeled by terms, which often include saturations, dead zones, and hysteresis. Designing control systems for such systems requires methods that can overcome these complexities as well as dominate uncertainties and nonlinearities. Nonlinear control theory therefore provides a solid foundation for modeling, analyzing and designing high-performance control systems that deliver excellent results. Traditional strategies such as linearization of the system around an operating point are not always sufficient to guarantee globally stable operation, it is therefore necessary to rely on more advanced strategies such as Variable Structure Control, [26].

A Variable Structure System (VSS) is a nonlinear discontinuous system, which can be regarded as a particular hybrid dynamical system since it is characterized by being piecewise continuous in different regions of its state space. A VSS behaves like different continuous nonlinear systems in different (disjoint and non-overlapping) regions of the state space. The dynamics of the system is characterized by a different structure in each of the regions. When the state trajectories of the VSS cross the boundaries of these regions, the structure of the dynamics switches. VSC indicates control methods that modify the dynamics of the system based on the region to which the state of the system itself belongs. Variable Structure in VSC refers precisely to the fact that the control law is not fixed yet switches depending on the region, thus making "variable" the structure of the controlled system. This aspect is markedly different than continuous controllers which maintain the same structure regardless of the state of the system. The great potential of the VSC lies in its ability to switch between control laws to ensure good performance and stability even in the face of system uncertainties and external disturbances.

Among the VSC strategies great importance is given to Sliding Mode Control (SMC) which defines and uses a unique concept known as "sliding mode". In the design of an SMC it is first necessary to define a sliding surface (sliding manifold) in the state space such that once the trajectories of the system belong to this surface the control objectives are satisfied. The system is in "sliding mode" when its trajectories reach and slide onto the sliding surface This motion of the system takes place on the sliding manifold, which is designed to provide the desired system performance. The main strength of SMC lies in its robustness. Once the system trajectories are on the sliding surface, they become insensitive to uncertainties or disturbances. This is achieved by using high-frequency switching control actions that force the system to stay on the sliding surface, [26].

To further clarify this, the sliding surface is generally represented by an equation $s(x) = 0$, where x denotes the state vector and $s(x)$ is the suitably designed sliding output. The aim of the control strategy is to steer $s(x)$ to zero in finite time and then keep it zero, thus ensuring that the system operates in "sliding mode".

However, a known challenge and major drawback of SMC is the phenomenon of chattering, which refers to high-frequency oscillations that can occur due to the practical implementation of discontinuous control laws. This can introduce unwanted effects into controlled physical systems. Various SMC modifications and solutions have been proposed to address this problem, leading to a wealth of research and innovation in this field, [26].

SMC has left a profound mark on modern control engineering due to its robustness and adaptability. It's a tool that has made it easier for engineers to handle the unpredictability of real-world scenarios, [29]. The sheer versatility of SMC has enabled its application across diverse sectors, from robotics and aerospace to automotive and power electronics. Let's delve deeper into the specific applications of SMC across these sectors, emphasizing its critical role in advancing technology and ensuring system efficiency and reliability.

1. **Robotics:** The domain of robotics necessitates precise and robust control mechanisms due to the complexities and uncertainties associated with tasks robots undertake. SMC has been instrumental in:

    - Manipulator Control: In industrial environments, robotic manipulators are tasked with handling materials with precision. SMC provides the necessary robustness against model uncertainties and external disturbances, ensuring accurate positioning and movement[29].
    - Mobile Robots: Autonomous mobile robots, especially those used in unstructured environments like disaster relief or planetary exploration, benefit significantly from SMC. It ensures that these robots can navigate and adapt to unpredictable terrains, ensuring mission success.
    - Swarm Robotics: As groups of robots work cohesively in swarms, the individual robot's behavior becomes crucial to the group's overall performance. SMC aids in the reliable coordination and formation control of these robot swarms.

2. **Aerospace:** The unpredictable nature of atmospheric conditions makes aerospace applications a prime candidate for the robust control that SMC offers. For example in:

    - Flight Control Systems: Modern aircraft, both manned and unmanned, utilize SMC to maintain stability and desired trajectories in the face of wind gusts, system failures, or other disturbances.

- Satellite Attitude Control: SMC aids satellites in maintaining their desired orientations in space. Given the high costs associated with satellite missions, ensuring robust attitude control is paramount[29].
- Spacecraft Docking: Automated docking procedures, such as those employed on the International Space Station, can benefit from the precision and robustness of SMC, ensuring safety and success in these critical operations.

3. **Automotive:** The automotive sector's push towards automation and enhanced safety has seen significant application of SMC.

   - Adaptive Cruise Control: Modern vehicles equipped with adaptive cruise control utilize SMC to adjust speed and maintain safe distances from vehicles ahead, ensuring smoother and safer rides.
   - Active Suspension Systems: SMC has been employed to develop suspension systems that adapt to road conditions in real-time. This not only ensures a comfortable ride but also enhances the vehicle's handling characteristics.
   - Traction Control and Anti-lock Braking Systems (ABS): Ensuring optimal grip and preventing wheel lock-ups during braking are critical for vehicle safety. SMC provides the necessary robustness in these systems, especially under varying road conditions[29].

4. **Power Electronics:** With the increasing reliance on renewable energy sources and the complexity of modern power systems, ensuring robust control is crucial.

   - Voltage and Current Control in Converters and Inverters: As power is converted from one form to another, ensuring the stability of voltage and current profiles becomes vital. SMC ensures that these profiles remain within desired bounds, even with system uncertainties or disturbances.
   - Grid Integration of Renewable Sources: Introducing renewable sources like wind and solar into the power grid comes with challenges due to their unpredictable nature. SMC plays a role in ensuring that these sources integrate smoothly, maintaining grid stability.

5. **Biomedical:** The delicate nature of biological systems requires control systems that are both precise and robust.
    - Drug Delivery Systems: Automated drug delivery, especially for critical medications like insulin, demands precise control. SMC can ensure that the right drug dose is delivered at the right time, even with uncertainties like varying patient needs.
    - Bio-mechanical Systems Modeling: As researchers aim to understand and model human bio-mechanics, control systems like SMC play a role in achieving accurate representations and simulations.
6. **Marine system:** Watercraft, both surface and sub-surface, operate in environments that are inherently unpredictable due to waves, currents, and other disturbances.
    - Ship Steering and Positioning: Modern ships, especially those used in precise operations like oil drilling, use SMC to maintain their position and orientation against environmental disturbances.
    - Submarine Navigation: Submersibles, both manned and unmanned, benefit from SMC's robustness, ensuring they can navigate and perform tasks reliably in the depths of the oceans.

The influence of Sliding Mode Control on modern technology is unmistakable. Its application across various sectors underscores its importance in ensuring system robustness, reliability, and efficiency. As technological systems grow more complex and operate in increasingly unpredictable environments, tools like SMC will be instrumental in driving innovation and ensuring operational success. Whether it's a robot navigating an unknown landscape, a car ensuring passenger safety, or a spacecraft executing a critical maneuver, SMC stands as a testament to the advancements in control engineering, promising a future where systems can adapt, perform, and excel regardless of the challenges they face.

6.2 Cyborg Insect SMC

In the upcoming section, we run into the process of designing a Sliding Mode Controller based on practical observations previously described. Through hands-on experiments, we've gathered a set of equations that accurately represent our system's behavior. Using this valuable data, we aim to craft a controller that aligns closely with our system's dynamics.

This approach ensures that our controller is both rooted in theoretical principles taken from other fields of study and fine-tuned to real-world performance. The model of the CI constitutes a new result in the relevant literature and the basis to design the control approach.

In fact, it is proposed the application of an automatic control, in particular a first-order Sliding Mode Control (SMC), [28], to a cyborg cockroach to perform desired trajectory tracking. Indeed, for these bio-systems the use of automatic control has not been widely investigated in the literature and constitutes itself an important novelty. Interesting results can be found regarding the tele-operation of CIs where the insect is controlled remotely by a human operator who monitors the cyborg's movements captured live by a webcam, [3], [31], or concerning an automatic control approach to maintain the insect moving in a delimited arena (without trajectory tracking) where the stimulation of the cerci is applied every time a stop of the cockroach is detected, [4].

6.2.1 SMC Problem Statement

The considered control problem is stated as follows.

It is assumed that the MHC equipped to be a CI is at time $t = 0$ in an initial position $(x_0, y_0) = (0, 0)$ coinciding with the origin of the $x - y$ plane. The control objective is to make the CI to get to a final target position $(x_T, y_T) = (x_D, 0)$, where x_D is a known constant, moving along the straight line connecting the origin to the final target point.

The stimulation of the antennae would have an effect on angular displacement producing oscillations in the trajectory, while it would not affect the forward motion of the CI.

Control objectives will be ensured only by the stimulation of the cerci according to the following SMC algorithm.

6.2.2 SMC for the MHC Trajectory Tracking

A SMC algorithm is designed to decide the input voltages signals V_{RC} and V_{LC} to be applied at each time instant.

There are two control objectives for the CI. The MHC must advance towards the final target point while remaining as much as possible on the x-axis.

Two sliding variables s_x and s_y are chosen as follows

$$\begin{aligned} s_x &= x - x_D, \\ s_y &= y, \end{aligned} \tag{6.1}$$

to define the sliding surface

$$\begin{aligned} s_x &= 0, \\ s_y &= 0, \end{aligned} \tag{6.2}$$

which guarantees the satisfaction of the two control objectives.

The following control switching logic is applied

$$\begin{aligned} &\text{While}\, s_x < 0 \\ &\qquad \text{If}\, s_y > 0\, \text{then}\, V_{RC} = 0\, \text{and}\, V_{LC} = \bar{V}, \\ &\qquad\qquad \text{else}\, V_{RC} = \bar{V}\, \text{and}\, V_{LC} = 0, \\ &\text{If}\, s_x \geq 0\, \text{then}\, V_{RC} = 0\, \text{and}\, V_{LC} = 0. \end{aligned} \tag{6.3}$$

Considering the kinematic equations (5.6), the control switching logic (6.3), and the sliding variable (6.1) the controlled state space is divided in two adjacent regions with different control structures (Fig. 6.1), which guarantee the condition $s_x \dot{s}_x < 0$ and $s_y \dot{s}_y < 0$ thus ensuring the asymptotic convergence to zero of both s_x and s_y.

The proposed SMC algorithm was implemented in the Simulink model of the MHC. A random number with mean 0 and variance 0.001 is generated and added to the state equations with cerci stimulation to account for the uncertainties and disturbances affecting the MHC model, [24], [9]. The mean and variance values of the normal distribution were found with the analysis of the experimental datasets.

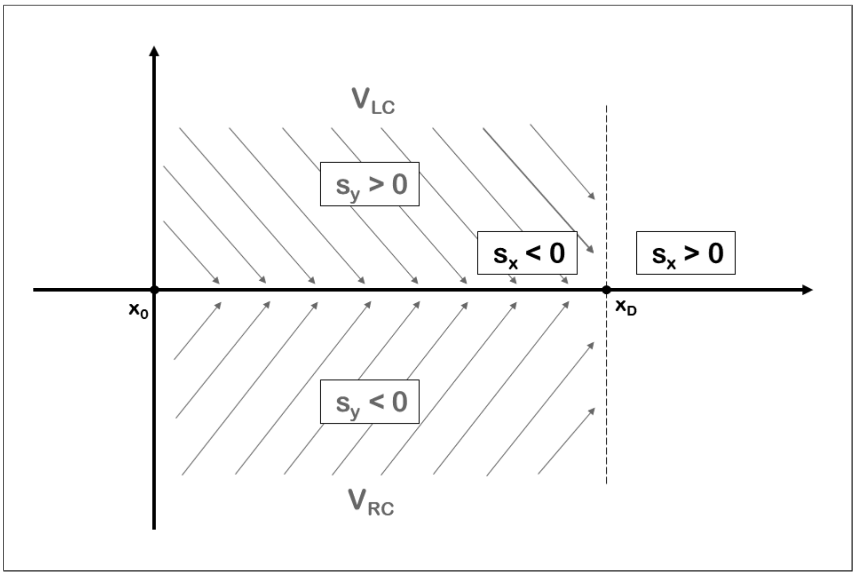

Fig. 6.1 The controlled state space divided in adjacent regions with different control structures.

The sliding mode controller switches according to (6.3) every $0.2s$, i.e. at a frequency of $5Hz$. The controller checks the sliding variables s_x and s_y, and keeps running as long as $s_x < 0$. If $s_y > 0$ (the cockroach is above the x-axis) the LC is activated and $V_{LC} = \bar{V} = 3V$; if instead $s_y < 0$ (the cockroach is below the x-axis) the RC is activated and $V_{RC} = \bar{V} = 3V$.

Simulations were performed over a time interval of $100s$.

In Fig. 6.2 can be noted that the CI controlled by SMC reaches the final target point along a trajectory (solid line) that always remains quite close to the x-axis.

Fig. 6.2 also presents the CI trajectory (dashed line) when the control approach proposed in [4] is applied to keep the MHC moving without tracking a trajectory. Simultaneous RC+LC stimulation is applied whenever a cockroach arrest is detected, [4].

Fig. 6.3 displays the state variables with SMC. Fig. 6.4 shows the convergence of the sliding variables s_x and s_y.

The graph of the inputs V_{RC} and V_{LC} is presented in Fig. 6.5. It can be noted that the controller stops functioning at $93s$ since $x_D = 3$ is reached and from that moment on $s_x > 0$. Fig. 6.6 shows the zoomed image of V_{RC} and V_{LC} in the range $17.2s$ to $18.6s$. The controller's switching frequency ($5Hz$) is clearly visible.

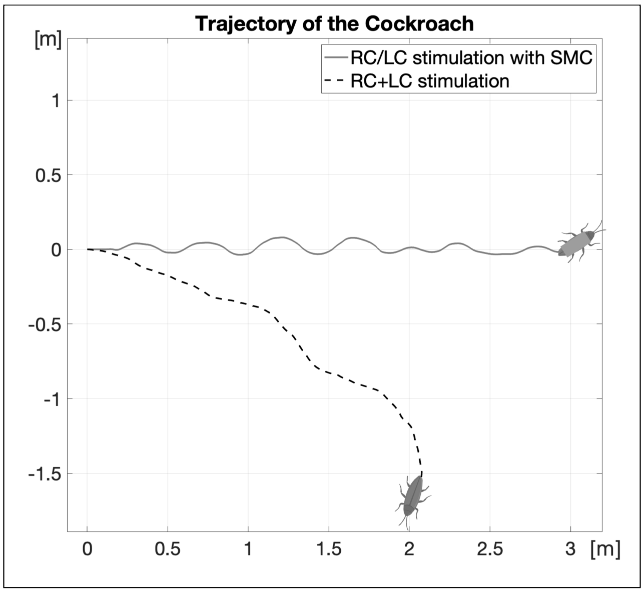

Fig. 6.2 Trajectories of the CI with the closed-loop RC/LC SMC command (solid line) and with the closed-loop RC+LC command proposed in [4] (dashed line).

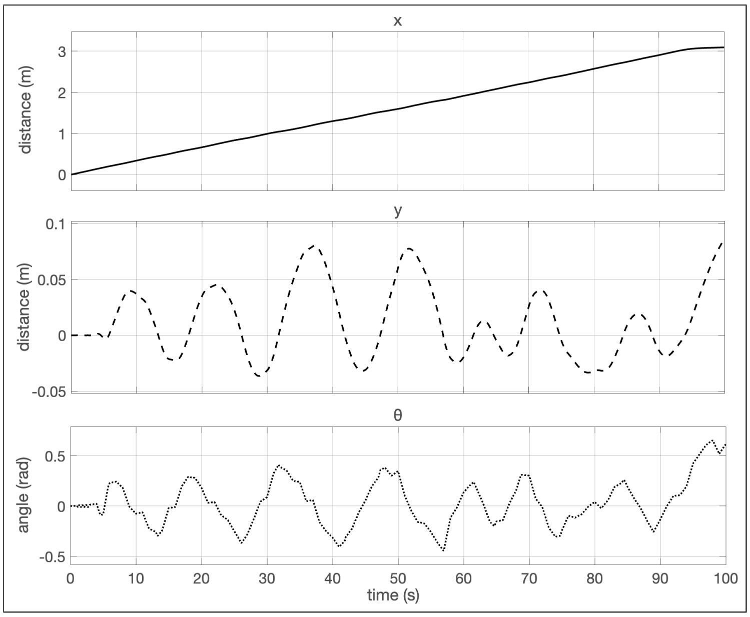

Fig. 6.3 State variables with SMC

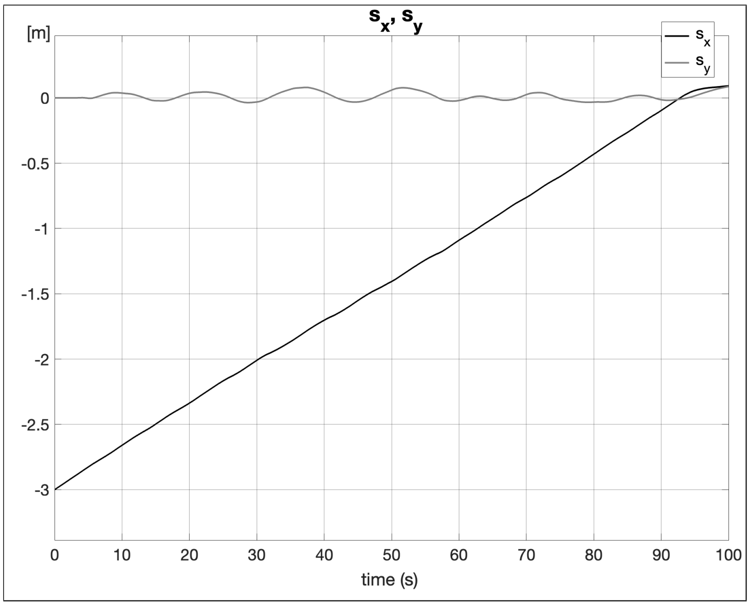

Fig. 6.4 Convergence of the sliding variables s_x and s_y with SMC.

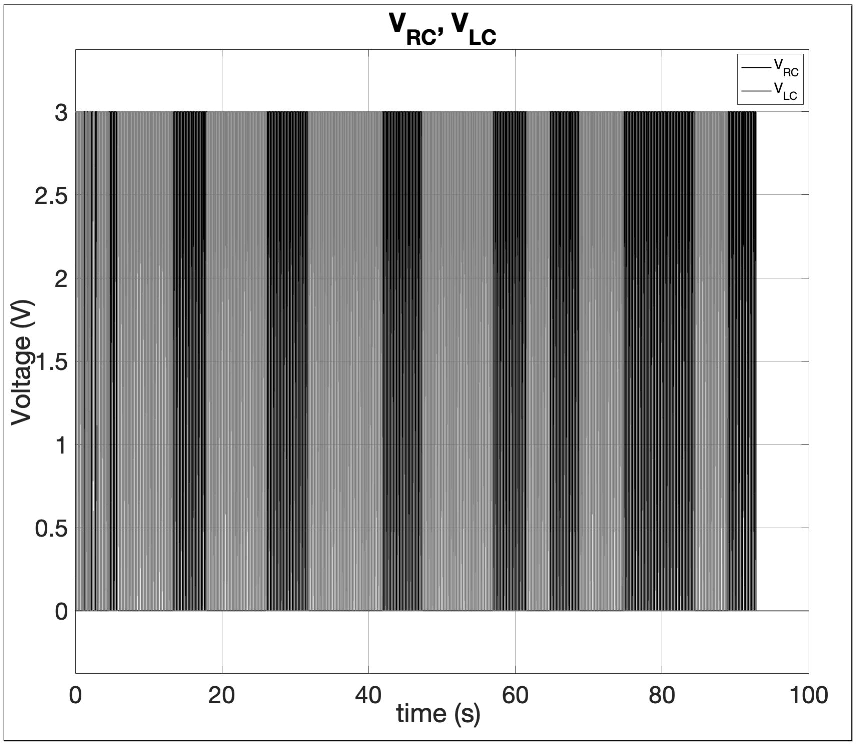

Fig. 6.5 V_{RC} and V_{LC} designed by SMC.

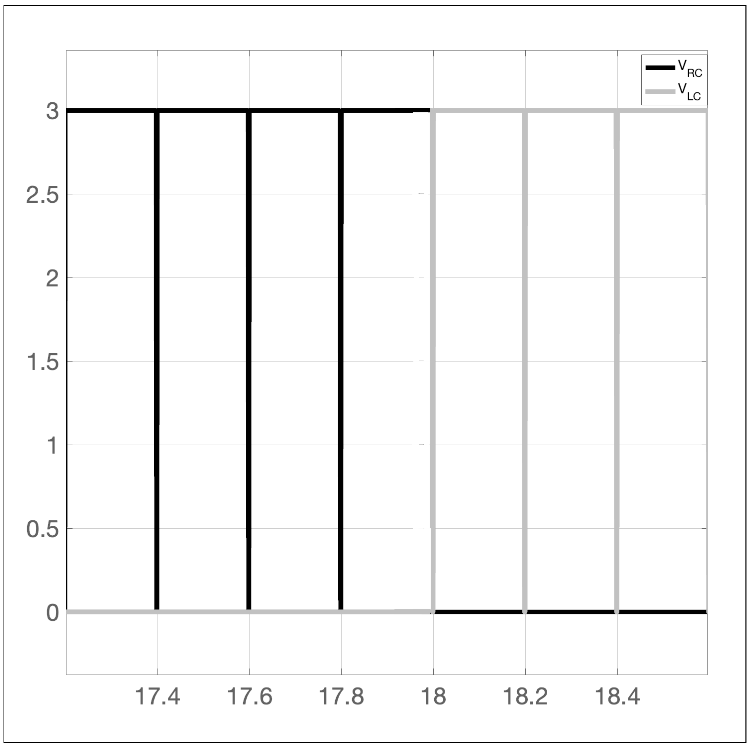

Fig. 6.6 Zoomed SMC V_{RC} and V_{LC} over a time interval of 2.2s.

Chapter 7

Conclusions

In this comprehensive thesis, we delved into the realm of bio-hybrid robotics, with a keen focus on the development of CIs, specifically utilizing the Madagascar Hissing Cockroaches as biological platforms. This fusion of biological entities with microelectronic components to manipulate and direct their locomotion has profound implications for a myriad of applications, ranging from advanced agricultural monitoring to intricate surveillance and even in the nuanced field of search and rescue operations.

An introductory section was written to present the state of the art for CIs research, presenting the different designs, including the one that was later used in the proper research.

The initial experiments focused on understanding the effects of different electrical stimulations on the cockroaches. Various parameters, such as the amplitude, frequency, and waveform of the electrical signals, were systematically varied to observe their impact on the insects' movement patterns. These tests were crucial as they provided insights into the optimal stimulation protocols that could elicit desired responses without causing habituation or undue stress to the biological component of the CIs.

Through this explorations, we gained valuable knowledge about the interplay between electrical stimulations and the locomotive behavior of the cockroaches. This understanding was instrumental in the development of the mathematical model and the subsequent design of the control algorithm. The findings from these initial tests laid the groundwork for further experiments, setting the stage for more sophisticated applications of Cyborg Insects in various fields.

In fact, we delved into the intricate task of modeling the behavior of CIs under various electrical stimulations, an endeavor that sits at the core of this research. The development of a comprehensive mathematical model was paramount to our understanding of how these bio-hybrid systems respond to external inputs. This model aimed to capture the non-linear dynamics of the cockroaches' movements, providing a predictive framework that could be leveraged to refine control strategies.

The controller design, particularly the implementation of a Sliding Mode Control (SMC) algorithm, represented a significant advancement in our ability to guide the CIs with precision. SMC is known for its robustness and efficacy in handling systems characterized by uncertainties and non-linearities, making it an ideal choice for this application. By employing this control strategy, we were able to achieve more accurate trajectory tracking in simulations, a critical requirement for the practical deployment of these bio-hybrid robots.

The next steps of this research could potentially include the real application of the Sliding Mode Controller on the Electronic Control Unit of the Bio-Robot, to test the correct functioning of the controller and check for non-modelled behaviors.

Looking to the future, the use of Cyborg Insects could have a wide range of applications. From monitoring crop health and detecting pests in agriculture to searching for survivors in collapsed buildings, the possibilities are vast. As we continue to enhance the control methods and deepen our understanding of these bio-hybrid systems, we can expect to see more innovative uses for them.

In conclusion, this thesis has shed light on a new direction in robotics, showing how the integration of biological elements with technological components can lead to creative solutions. The work presented here lays the foundation for further research and the development of Cyborg Insects for various tasks, promising an exciting future for the intersection of technology and biology.

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Appendix A

Simulink Model Description

In this appendix, we expand on the Simulink model discussed in Chapter 6, providing a visual and detailed perspective through annotated screenshots. The aim is to elucidate the model's architecture and operational logic, breaking down its components and their interconnections. This visual guide not only complements the theoretical explanations from Chapter 5 but also delves into the reasoning behind the model's design, shedding light on the selection and arrangement of its components.

A.1 Main Simulink Framework

The main Simulink Framework is shown in Figure A.1. It is composed by the main block (Cockroach D) with its 4 inputs: V_{RC}, V_{LC}, V_{RA}, V_{LA}, which respectively represent the voltages on the Right and Left Cercus and on the Right and Left Antenna. There is also the possibility to activate the contribution of the Sliding Mode Controller with the "A" and "B" signals. From the Main Model, the outputs are $\dot{x}$, $\dot{y}$, $\dot{\theta}$, that are then passed through an integrator block that give out respectively the position coordinates x and y and the orientation of the cockroach θ, that are then printed on a scope or used to generate a picture of trajectory of the modelled CI.

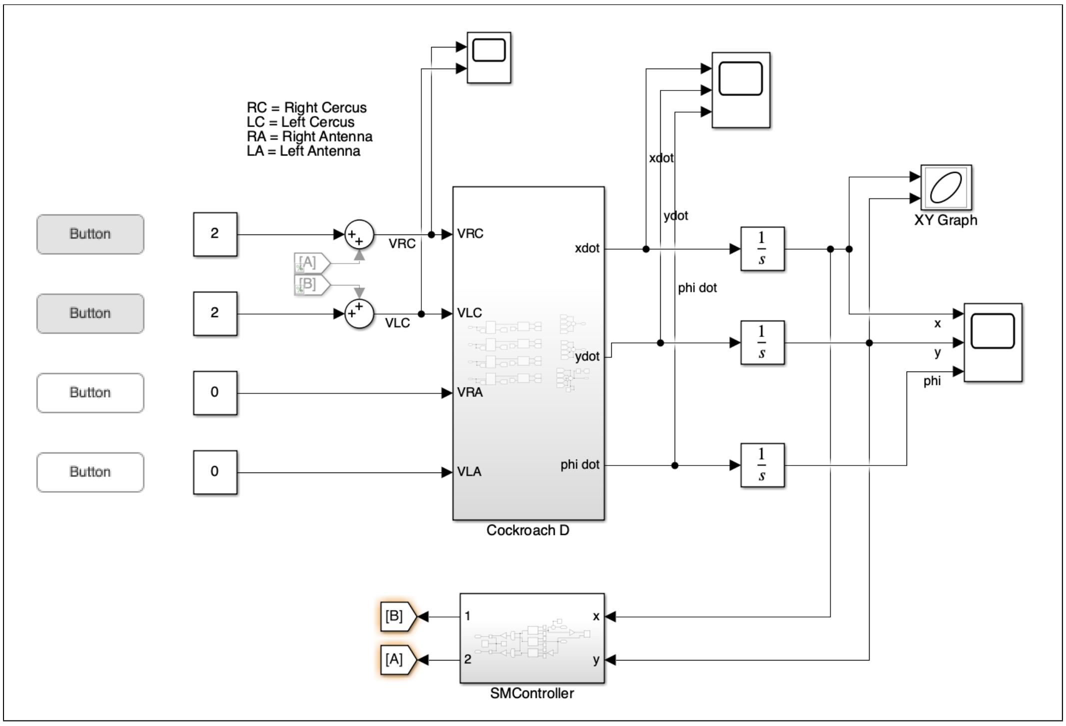

Fig. A.1 Main Framework of the CI Model.

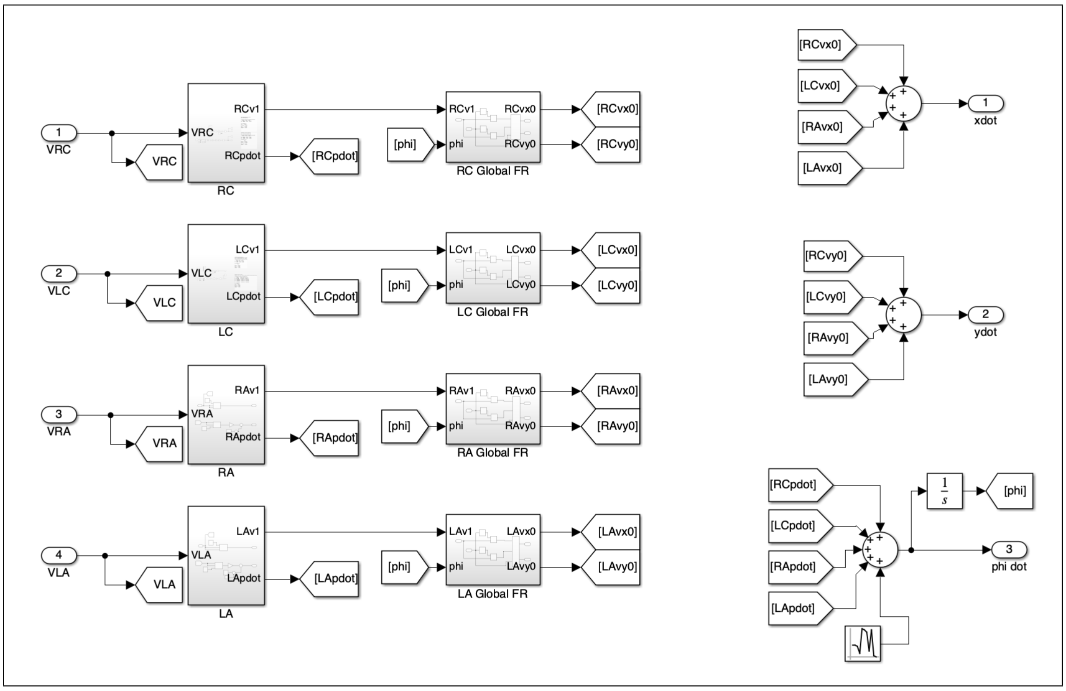

Fig. A.2 Internal Logic and Math of the CI Model.

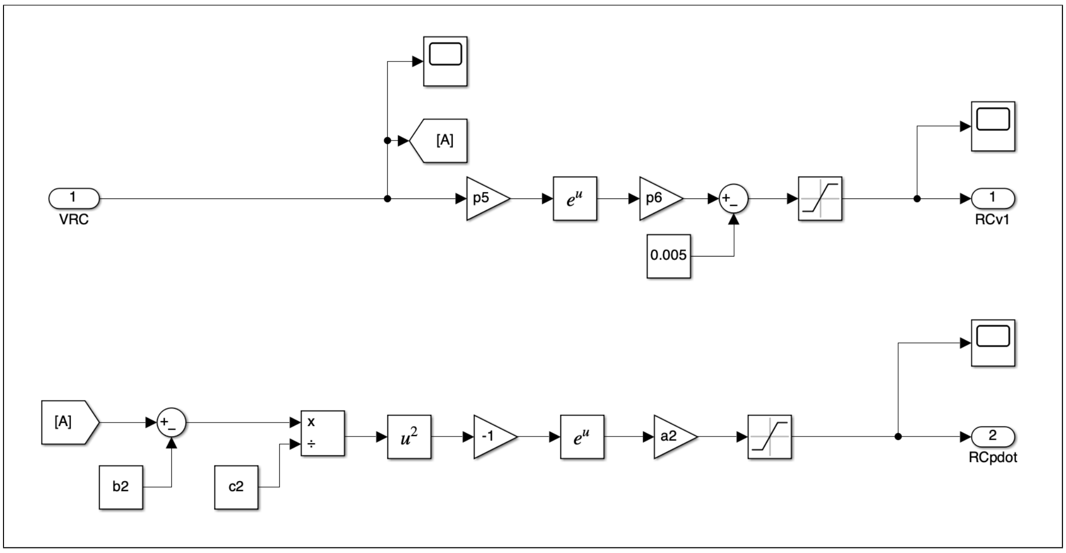

Fig. A.3 Modelled Equation 5.2 in Simulink.

A.2 Cyborg Insect Model Block

This section describes the main window in which the internal logic and math of the CI was modelled (shown in Fig. A.2). The inputs are as always the 4 antennae that the real cockroach would sense its environment with: V_{RC}, V_{LC}, V_{RA} and V_{LA}. Each signal first goes through the "Equation Block" which is described in section A.3 (specifically the RC Equation Block). After that, the signals go through the "Local-to-Global Frame Block" which transforms the signals from a mobile frame of reference to the global one in order to sum the different contributions later. The description of this block is done in section A.4. Lastly in this block, all of the contributions coming from the different inputs are summed to give out the 3 outputs of the model, as already explained in section A.1, which are: $\dot{x}$, $\dot{y}$ and $\dot{\theta}$.

A.3 Equation Block

This block represent the translation of the experimental equations that were described in section 5 for the trajectory of the Cockroach. In Figure A.3 specifically, equation 5.2 is modelled, but each equation for V_{LC}, V_{RA} and V_{LA}, found in the same section of the thesis, are equally modelled in the Simulink system. In Figure A.3 the model takes the input voltage coming from the Right Cercus and through a set of

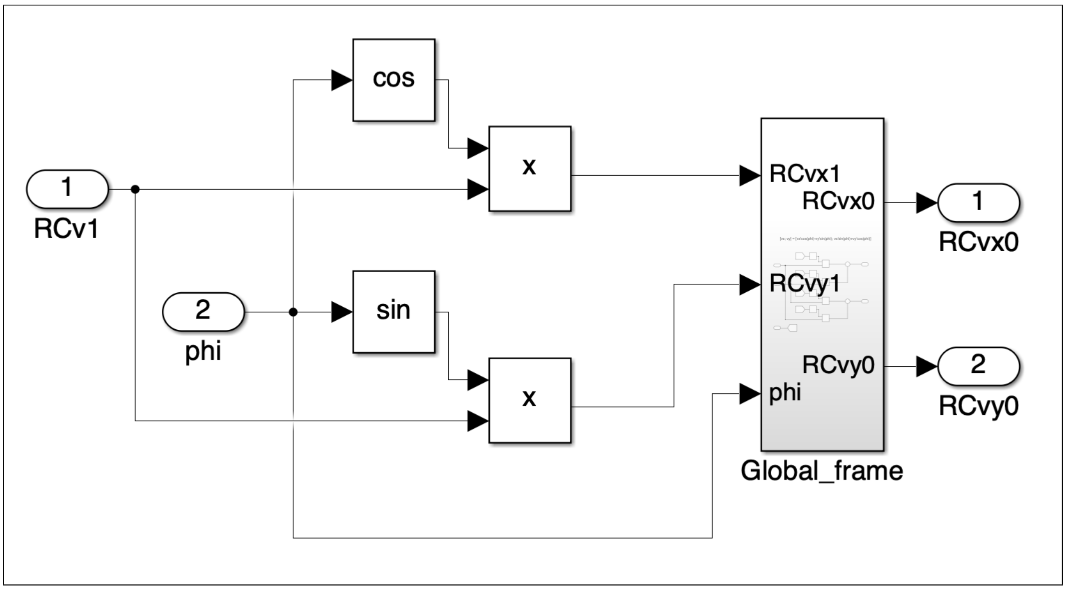

Fig. A.4 Simulink block which transforms the values of velocity due to RC stimulation into its *x* and *y* components.

mathematical operations, outputs the contribution to the linear velocity and angular velocity of the CI in the mobile frame of reference.

A.4 Local to Global Frame Block

Fig. A.4 shows the block that takes as input the velocity contribution given by the stimulation of one of the 4 antennas of the CI (in this case from the Right Cercus). After splitting the value into its vector components on the *x* and *y* axes, they all go thorugh another block which is here represented in Fig. A.5. This block will transform the local coordinates into global coordinates through the following equation:

$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} = \begin{bmatrix} v'_x cos(\theta) - v'_y sin(\theta) \\ v'_x sin(\theta) - v'_y cos(\theta) \end{bmatrix} \tag{A.1}$$

As already stated in section A.2, each velocity value of velocity that enters into the Local-to-Global coordinates block, gives out its 2 projections on the *x* and *y* axes and according to the global frame of reference.

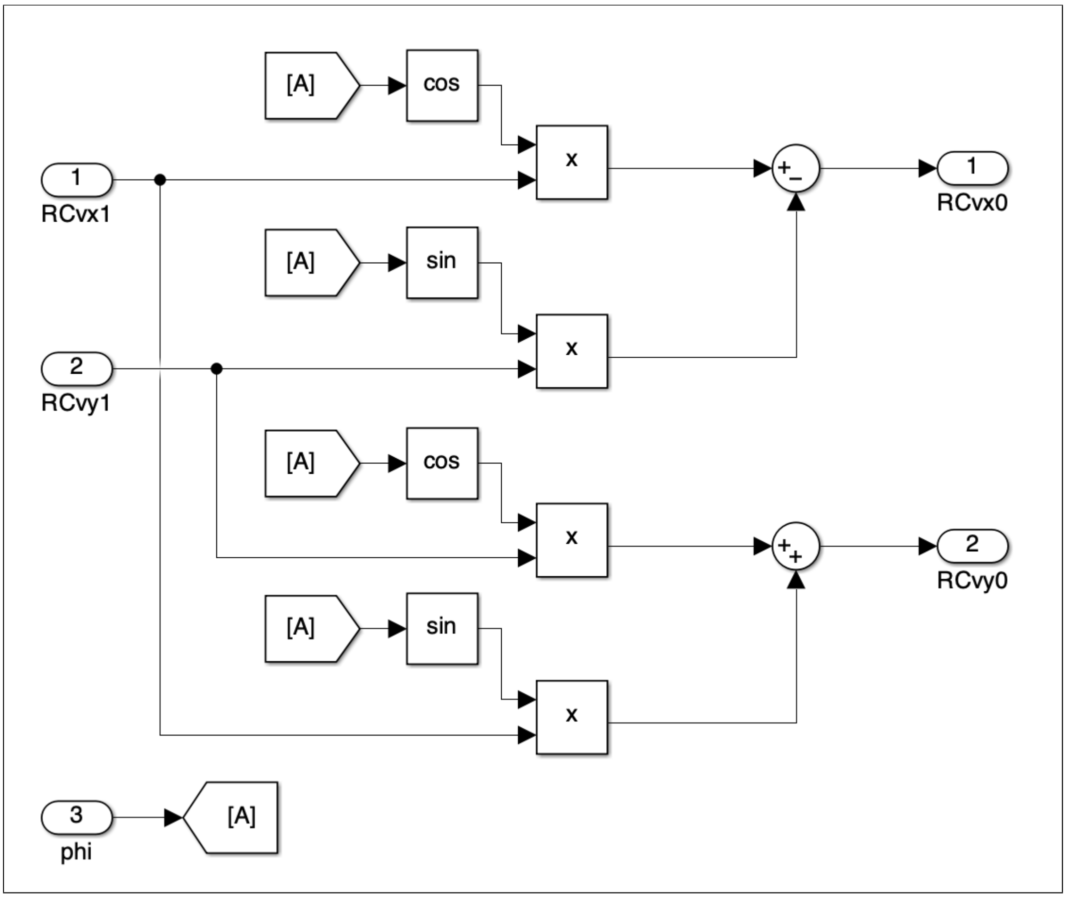

Fig. A.5 Simulink block which transforms the values of the components of velocity from a local to the global frame of reference.

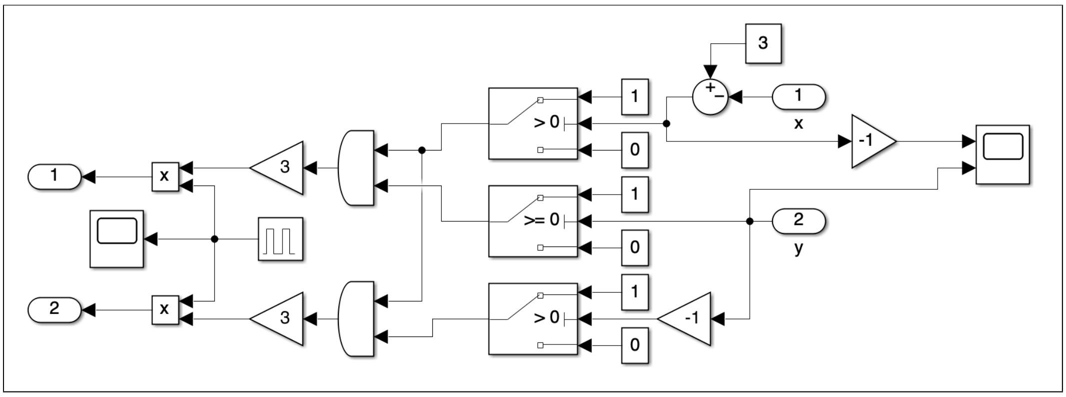

Fig. A.6 Simulink block which shows the logic behind the SMC described in section 6.2.

A.5 Controller Block

The controller block showed in Fig. A.6 represents the internal logic and math of the Sliding Mode Controller already described in section 6.2. This model allows the user to choose different values to make the controller more or less sensitive and it also allows it to work at different values of frequency to, for example, potentially stress the real insect less or to adapt to the speed of the hardware.