

InsectArcade: A hybrid mixed reality insect-robot system for the study of insect multi-modal navigation

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Chapter 1

ABSTRACT

Insects are great explorers. With their small body size, insects perform excellent navigational tasks through specialized behavior. Insects and mobile robots share similar tasks. Both have to navigate within dynamic environments to reach a specific place. Despite the scientific interest on insect behavior, morphology, ecology, and nervous system, it still remains unknown how insects integrate simultaneous sensory stimuli during navigation. One problem could be that we are lacking on computational systems to study insect behavior. To investigate insect multi-modal integration during navigational performance we have built InsectArcade - a multi-sensory environment that is able to immerse an insect into a virtual arena and at the same time interfaces it with a mobile robot. The apparatus is composed by a floating trackball surrounded by computer screens showing a virtual environment. When an insect walks on top of the ball, the ball rotations are translated into movements of both the virtual environment and the movements of a robot. Sound and electrical stimuli were added and mapped into the virtual environment. In this report, we broadly describe the insect ecology, behavior, and nervous system architecture, to contextualize the development of insect hybrid systems. We will describe the properties and components of the proposed system. We present initial data to show the validity of this environment as a tool for testing insect behaviour and sensory integration during navigation tasks. Such hybrid system allow us to test how crickets weight visual stimuli while performing phonotaxis navigation within virtual environment tasks. We present data regarding the ability of crickets to perform contextual learning within virtual environments, as well as a validation of the insect controlled robot application.

Keywords: Insect behaviour, navigation, cricket (*Gryllus bimaculatus*), insect nervous system, multi-modal integration, sensory-motor loops, hybrid systems, robots.

Chapter 2

INTRODUCTION

Insects are able to navigate robustly in very dynamic environments with limited resources, while their robotic counterparts are not able yet to demonstrate strong navigational skills in comparable scenarios. At the sensory-motor level, insects and mobile robots face similar problems in the real world. Both insects and autonomous robots need to integrate multi-modal stimuli, and constantly adapt to a dynamic world in order to navigate successfully. The relatively simple insect brain has been the subject of research aimed at revealing the mechanisms behind insect navigation. Nevertheless it still remains unclear how insects integrate sensory information and acquired knowledge. In this thesis project, we propose InsectArcade - an insect-robot hybrid system designed specifically to analyse insect navigational behaviour within a multi-modal mixed reality environment. In the follow report we will describe the general insect nervous system architecture, but focus on the cricket (*Gryllus Bimaculatus*) specific behavior and specialized body morphology. The presented data serves to validate the InsectArcade system. To test the ability of crickets to integrate different sensory modalities, we tested the navigation performance of adult female crickets stimulated by a visual virtual object coupled to the sound source. To do so, we will reveal the female cricket behavior when immersed within a virtual environment and stimulated by a real-time synthesized cricket male calling song. One major advantage of using virtual reality environments is that it allows to test insect navigation, while remaining at a fixed distance and orientation of the sensory stimuli source. Also, it assures a controllable environment regarding stimuli and animal position at each time, facilitating the tracking and analysis of experiments.

2.1 Problem statement

Insects have a simpler nervous system architecture when compared with mammalian neural anatomy. Although, they are able to integrate multi-modal stimuli and achieve optimal results when performing navigational tasks. Mobile robots, on the other hand, still have difficulties on the integration of sensory stimuli when navigation in real world dynamic environments. As most of insects, crickets present species-specific behaviours and specialized body architectures. Moreover, crickets have a proper size to run experiments that imply deal with the animal body (when compared with smaller animals such as ants). Such characteristics makes them ideal animals to validate our hypothesis. Crickets are able to make use of visual cues to detect specific spots[6], and to perform the described phonotaxis behavior to detect a sound-source position. Even though certain neural structures as the Mushroom bodies or Central Complex[17] are usually pointed to play a crucial role on the integration of multi-modal information in insects, the dynamics of the gains and priorities for each modality still remains unclear. The goal of our project is to develop a tool to quantitatively study the integration of different sensory modalities while performing navigational tasks in a controlled apparatus. Moreover, we plan to investigate the relevance of specific modalities during insect navigation by testing the integration of sound and visual information on female crickets, and how such information is used by the animal to perform contextual and behavioural learning.

2.1.1 Hypothesis

We expect that cricket weight more the auditory stimuli rather than visual cues, while performing virtual environment navigational tasks. Although, we assume that visual cues improves the time needed to perform such task.

2.2 State of the art

2.2.1 Background on insect nervous system

In general, the insects nervous system is adapted to specific tasks. Although their neural circuitry is mainly formed by reflex-loops, insects display many more than only pure reactive behaviours. Insects perform complex tasks such as pattern recognition and context dependent learning and most of their behaviours imply successful integration of information from different sensory modalities [15]. Earlier research suggests that parallel direct sensory-motor loops are supplemented by specific brain areas that serve to integrate

functions relating to context, learning and smooth coordination of action [15]. In this context, emphasis is often placed on the role of the mushroom bodies in the integration of sensory stimuli and motor signals. Indeed, the neural responses in the mushroom body appear to be correlated to specific directions of the animal's turning behaviour [10]. Crickets, for instance, have a specialized nervous system to deal with sound. Female crickets are able to locate a mate through phonotaxis [12]. However, crickets, and other insects, also use egocentric and allocentric navigation systems to perform homing tasks [13, 8, 7], and that visual landmarks are used to improve cricket place memory [6].

2.2.2 Insect nervous system architecture

Several insect behaviours imply the integration of signal from different sensory modalities, the performance of contextual learning (e.g.: homing, or path integration [23]), and the coordination of coexistent other behaviours ("negative phototaxis is coupled with thigmotaxis in finding suitable shelter" [18 (p.147)]). Insects are provided of diversified sensory channels to perform specific functions. Insect nervous system architecture presents a general pattern among different insect species. Certain anatomical areas such as the Mushroom bodies or the Central complex are usually pointed as responsible of integration and control of multiple sensory-motor mechanisms [10, 15, 17]. Insect nervous system consists of a nexus of large aggregates of neurons (ganglion). Their external anatomy is composed by the Head, the Thorax, the Abdomen and the Appendages.

The insect brain is composed by two ganglias: the supraesophageal ganglion, and the subesophageal ganglion [16]. The supraesophageal ganglion (where secondary and tertiary auditory inter-neurons of female crickets are placed [19, 20]), is composed by the proto-cerebrum, deuto-cerebrum and trito-cerebrum. The proto-cerebrum carries the optic lobe (dedicated to receive input from insect compound eyes and ocelli receptors) and also anatomical areas as Mushroom bodies and the Central complex. The deuto-cerebrum consists of the antennae lobe and antennae mechanosensory and the motor centre, since it is responsible for the antennae information processor. The trito-cerebrum is responsible for the sensing, perception, and motor control of the mouth-parts. The subesophageal connects the supraesophageal ganglion to the ventral nerve cord.

The Thoracic ganglion (in the Thorax of the animal's body) is responsible for the control and coordination of appendages (wing and leg) movements. Also, it receives sensory information from the appendages through mechanisms as proprioception and mechanoreception. The leg-specific thoracic

ganglion is controlled by both Proprioceptors and Exteroceptors mechanisms. Proprioceptors receive input from the legs joint angles and muscle contractions. Exteroceptors receive input from exterior receptors such as hair (touch) sensor placed on the animal's foot. To perform such functions, the Thoracic ganglion takes advantage of both "descending" and "ascending" axons [16, 21, 22].

The Abdominal ganglia receives mechanosensory information from insect's dorsal receptors. Cerci hair-cells, for example, are composed by tactile hairs sensitive not only to touch, but also to air flow, vibrations of the ground, or low frequency sound waves.

In the insect ventral nerve cord, each aggregate of neurons receives sensory input and simultaneously controls respective body parts. In fact, several insect behaviours (e.g. phonotaxis in crickets [18 (p.310)]) are controlled by body ganglion (ventral nerve cord) in place of the supraesophageal ganglia. At the sensorymotor level, insect behavior is frequently described as complex of parallel but integrative and specialized sensorymotor interactions.

Air movements detection by Cerci hair-cells, for instance, is performed through direct connectivities from the abdominal ganglia to the thoracic ganglia [24]. Cricket phonotaxis performance (auditory localization), for instance, processes both descending and ascending transmission between the thoracic ganglia and the brain (specifically, the supraesophageal ganlion) [20].

Brooks assumption[25] that a complex of task-oriented processes with individual sensor, control, and actuator mechanisms form the bases of a behaving system, could be accessed to describe insect nervous system and behaviour. Insect nervous system architecture allows to the (reflexive-loop) interaction of different behaviors, prioritizing and/or integrating each of them. Moreover, insect nervous system architecture is provided with several types of interaction among its reflex-loop processes. Both top-down (sensory activation, sensory neurons, sensory inter-neurons (or ascending neurons), brain or specific nerve cord ganglion) and bottom-up (brain, motor inter-neurons (or descending neurons), motor neurons and muscles) flow of information are necessary to perform behavioural outcomes.

2.2.3 Cricket morphology and behavior

Within the cricket ecology, male and female cricket bodies differ in terms of structural morphology. The female cricket has a developed auditory system for matting proposes while the male makes use of its developed forewings to generate an attractive sound [26, 27, 28]. Female crickets are able to find a mate that belongs to the same species by moving in the direction of a species-specific calling song generated by the male - phonotaxis behavior

[18(chapter 10), 26, 27]. Female cricket auditory apparatus consists of one ear (tympanum) on each one of the two forelegs, and they reactively turn to the side that is more strongly affected [18 (chapter 12)]. Although the apparently simplicity of such behavior, the problem to detect which ear is closer to the sound source implies more than the analysis of sound amplitude. Cricket tympanums are distanced between one and two centimetres of each other. Since the wavelength of the male generated sound has an amplitude of approximate 6.533 cm (when in 20C dry-air conditions ($\lambda = C / F$), λ : wavelength (in meters); C: sound-speed; F: sound-frequency), there is no amplitude difference between the animal ears. In the auditory apparatus of the female cricket, a peripheral mechanism connects the tympanum to the spiracles (two entrances on the top of the head) through a air-filled tube (the tracheal tube), creating a gradient pressure detector. The tympanum receives the sound both externally and internally. Thus, the direction of the sound is detected by the movements of the tympanal membrane, which depends on pressure gradient direction [29, 30]. The male cricket produces it's species-specific calling song by scraping both forewings, and resonating through a series of impacts between the plectrum and several teeth of the file placed in interior and exterior part of the wing, respectively. The male produced sound consists of a species-specific sound which by it's specific properties allows the female cricket to detect the sound source.

Within the cricket ecology, female preference of sexual selection varies among different species, and even, among individuals of the same population [31]. Moreover, it has been showed that several parameters of the male cricket calling-song, such as call frequency, frequency bandwidth, chirp period, or syllable period, are tracked by the female cricket [18]. Thus, it is suggested that pattern recognition for sound localization is performed through neurological mechanisms and that sound localization modulation is done through auditory steering [33].

2.2.4 Insects and hybrid-systems

Besides field experimental studies to study insect behaviour a number of different paradigms have been proposed to perform behavioural experiments. Measurements of insects phonotactic responses have been tested using locomotion compensator, in specially the Kramer spherical treadmill [32]. Locomotion compensation apparatus have been extensively used to study insect navigation since the late 1960s [5, 1, 11]. Also mixed reality closed-loop systems were proposed to analyse cricket antennae movements [11, 16]. Similar approaches have also been generalized to vertebrates [3]. Such locomotion compensator apparatus, allow to test the animal movements towards the

stimuli source, keeping the stimuli parameters at a constant level. Another experimental platform for analysing insect adaptability used a robot controlled by a male silk-moth to manipulate interactions between the animal and its environment while performing sex-pheromone chemotaxis [4]. Insect-robot hybrid systems have been developed to study animal behaviour in a range of navigation tasks, for instance, phonotaxis [14]. The Locomotion compensator apparatus is one plausible tool for investigating animal navigation within controlled environments. Adding mixed-reality mechanisms increases the amount, complexity and ecological validity of possible stimuli that are used during the experiments. Also, using such an apparatus to control mobile robots seems to be a way to map an animal behaviour into a robot behaviour enhancing the ability to analyse the specifics of motion. With our system, we expect to advance the properties of these integrated experimental set-ups as a further step in the development of Insect-Robot Hybrid Systems. Moreover, we expect to combine properties of the described set-ups into one integrated system. Such approach allows keeping the insect into a controlled environment while the robot navigates within a real arena.

Chapter 3

METHODS

3.1 The InsectArcade system

With proposing an insect hybrid system we aim at providing a tool to quantitatively test insect navigational capabilities within a controlled mixed-reality environment. Our hybrid system's architecture is composed of two main parts: the multi-modal mixed-reality apparatus (Figure 3.1), and the insect-controlled mobile robot. The apparatus consists of a polystyrene ball with a diameter of 7.5 cm floating on an air cushion where the insect moves on its top or rests. Two optical sensors, placed at 90 of each other pointing to the center of the sphere, track its rotations when the animal walks. The insect is tethered to a rigid beam in such a way that it remains placed on the sphere in the same position. Four computer screens are placed around the sphere to provide 360 visual stimuli (Figure 3.2).

The mixed reality insect-robot system allows a fifth computer screen on the top. Since we were dealing with nocturnal animals, we decided to provide the minimal light conditions for a virtual navigation task, therefore we used three displays (front-view, left-view, right-view). A virtual environment was developed using OGRE (Object-Oriented Graphics Rendering Engine, MIT license) an open source 3D engine where landmarks, ambient light or other graphical properties can be manipulated in a controlled fashion. A PureData (IRCAM, Paris) sound application was integrated to generate insect specific calling-sounds. Two loud-speakers (TEAC AMERICA, Inc., Tokyo) were placed at 35cm distance from the sphere, at 45 from the front of the animal, to provide stereo sound stimuli to the animal. Visual and auditory modalities are coupled in an environmental consistent fashion. Furthermore in order to test the contextual or behavioural learning capability of the animal

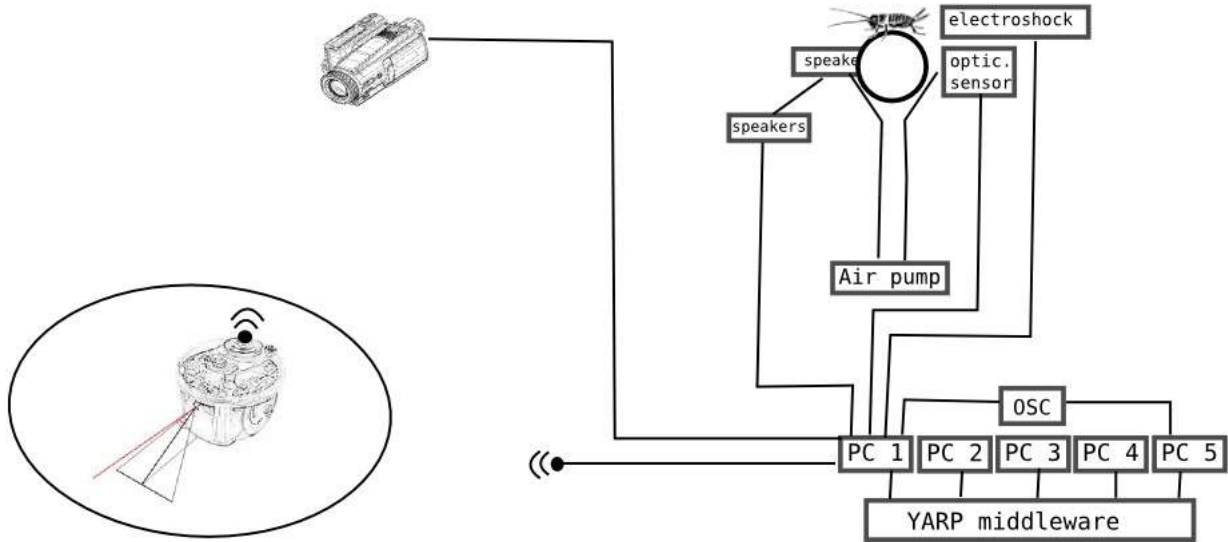


Figure 3.1: **System diagram without the representation of displays.** An insect, on the center, controls the floating sphere that is connected to the air-pump. Pc 1 connects the system components. An insect-controlled-robot application translates the insect movements into the robot movements through a video camera and a bluetooth signal emitter, on the left.

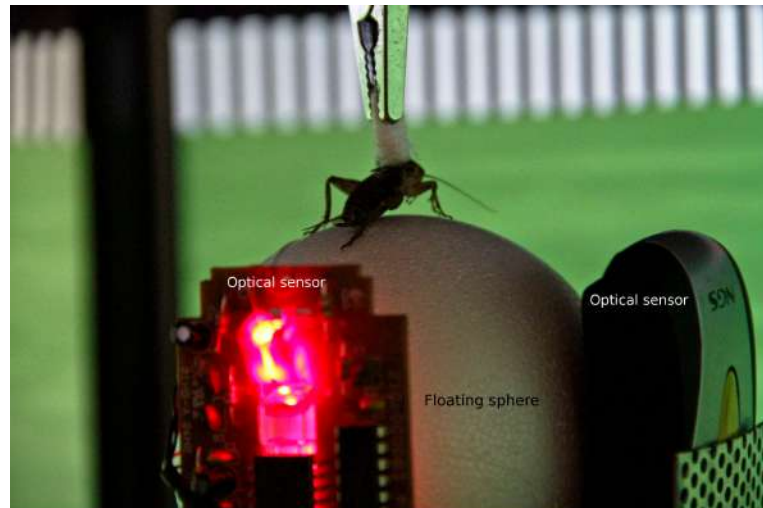


Figure 3.2: **Closer view of system's apparatus.** A female cricket navigates on the virtual environment. Two optical sensors read floating sphere rotations on its three degrees of freedom (yaw, pitch, roll).

an electroshock delivery system was developed. Aversive stimuli are effective reinforces for contextual learning [2]. The electronic circuit comprises a set of resistors (ranging from 1k to 42k), controlled through a Peripheral Interface Controller (PIC - micro controller, Microchip Technology, Chandler, Arizona). This circuit allows correlating the insect's position in the virtual world or specific movements with the delivery of electrical current. We use the YARP middle-ware [9] to allow the integration of most of the components of the system and synchronize the different computer systems. This middle-ware open-source software library allows us to define data flows between individual software applications. A small robot (16cm x 11.5cm) was built to integrate our Insect-Robot Hybrid System. The movements of the robot are controlled by the insect behaviour. The robot is composed of two servo-motors, one free-wheel, one Arduino Nano board (ArduinoTM) (for signal processing), an Xbee wireless module (4214A-XBEE, MaxStreamTM), for robot/computer communications, and one wireless camera (Aliveal, Hsin Tien City). A video tracking system is used for monitoring the robot's behaviour according to the insect's position in the virtual environment. Thus, by tracking the animal's position and orientation in the virtual environment, we are able to set the robot's position and orientation in the real arena as well. Our set-up allows the insect to navigate within the virtual environment using a egocentric perspective. The Insect-robot Hybrid System operates in an open- loop fashion, where the system's sensory stimuli are provided to the animal and the animal's behaviour is used to control the mobile-robot. The system has been conceived to run insect-robot experiments in parallel. Thus, a direct mapping between the insect and robot behaviour should be achieved for sensory integration and for the analysis of environmental conditions. In addition, it allows us to couple the sensor data of the robot to that of the insect.

The technical features of InsectArcade are presented in table 3.1 and compared it with the set-ups used by Yamashita et al. (2009)[11] and by Shiramatsu et al. (2010)[16].

InsectArcade - Shiramatsu - Yamashita			
compesator material	Styrofoam	Styrofoam	Styrofoam
sphere dimensions	7,5cm	7,5cm	7,5cm
floatting support	air	air	air
number of displays	4	1	1
movements sensor	optical	optical	optical
visual content	3D	3D	3D
antennae track.	no	yes	no
sound stimuli	yes	no	yes
real-time sound generation	yes	no	no
electroshock stimuli	yes	no	no
real robot extension	yes	no	no

Table 3.1: **Comparing the InsectArcade with two other Insect hybrid systems.**

InsectArcade is an autonomous system composed by specific hardware and software architectures. Hopefully, the combination of those architectures will allow to define the InsectArcade as a scientific apparatus for the study of insect multimodal integration during navigational tasks.

3.1.1 Hardware description

System structure

The InsectArcade is build on a metallic structure (210 cm x 90 cm x 100 cm) surrounded by polystyrene surfaces to avoid external light and sound reflection (Figure 3.3).

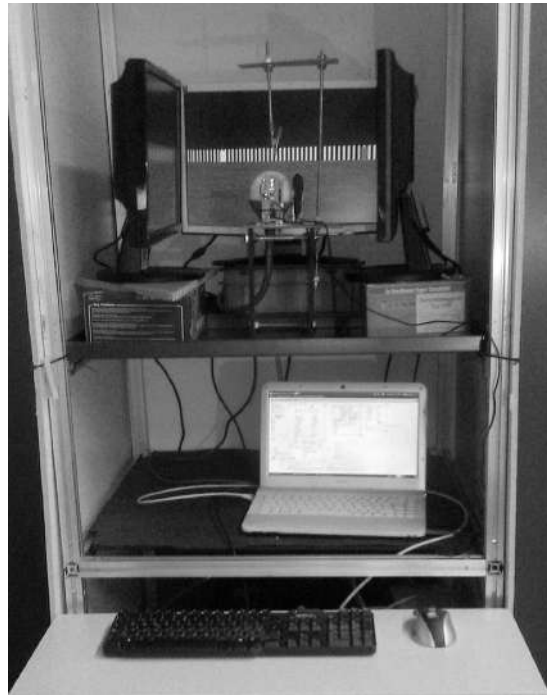


Figure 3.3: **System structure without back-display.** Four displays on the top surround the animal. One computer (down), connects the system components with insect-robot application (not represented in here).

Locomotion compensator apparatus

The Locomotion compensator apparatus (40 cm (height) x 30 cm (length) x 30 cm (width)) is composed by a wooden structure and an acrylic surface (Figure 3.4). A conic object is in the center of the apparatus connected to the air-pump through a rubber tube (1 cm diameter), allowing the polystyrene sphere (75cm diameter) to float and rotate on the top of it but keeping the same position. Two optical sensors are placed at 90 of each other pointing the center of the sphere in order to detect sphere rotations on its three degrees of freedom. A vertical bar with forceps on the bottom was integrated and centred to hold the animal on the top of the sphere.

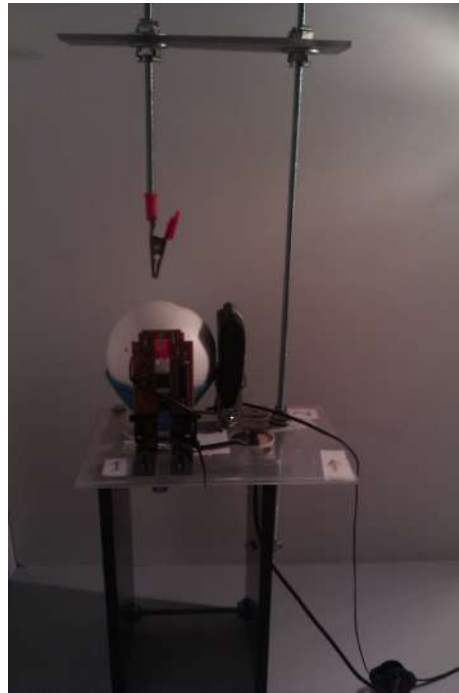


Figure 3.4: **Closer view of the locomotion compensator.** An acrylic surface holds the floating sphere, two optical sensors, the forceps to secure the animal, and the air-tube entry.

The Insect controlled robot

The insect-controlled robot (Figure 3.5) with the dimension of 16cm x 11.5cm was built with the minimal components of a robotic structure:

- signal receptor (4214A-XBEE, MaxStreamTM),
- processor (Arduino Nano board (ArduinoTM), Ivrea, Italy),
- wireless camera (Aliveal, Hsin Tien City),
- battery (NiMH, 4,8 volts, 880 mAh ,SANYOTM),
- two servo-motors (Hitec 32065S HS-65MG Metal Gear Feather Micro Servo Motor, Hitec RCD Inc. Poway, USA),
- two wheels (5cm diameter),
- one free-wheel (0.8cm diameter),

The robot is programmed using the Arduino language and behaves accordingly with the parameters arrived from the "robot application", which in turn gets input from the virtual environment.

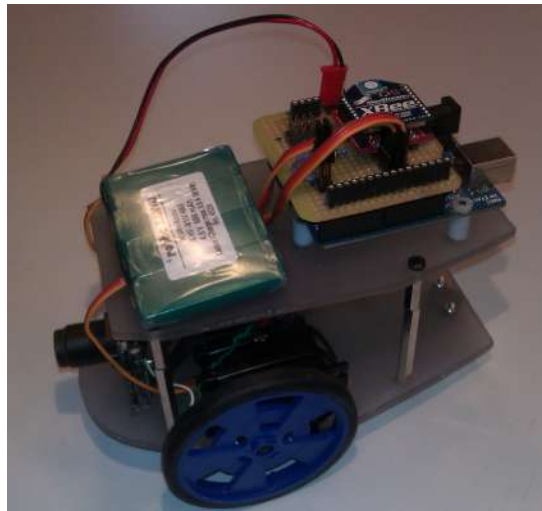


Figure 3.5: The insect controlled robot

Electroshock delivery system

The electroshock circuit was developed to receive input from the virtual environment application, and output one of ten possible electrical current states accordingly with the insect position within the virtual environment. Ten resistors (ranging from 1k to 42k) and ten accumulators were integrated into the circuit and connected to the Peripheral Interface Controller (PIC - micro controller, Microchip Technology, Chandler, Arizona). The micro controller was programmed in the C programming language and allows to a continuous electric signal output. The follow pictures show the electronic circuitry design (Figure 3.6); the circuit modelling (Figure 3.7); and final prototype (Figure 3.8).

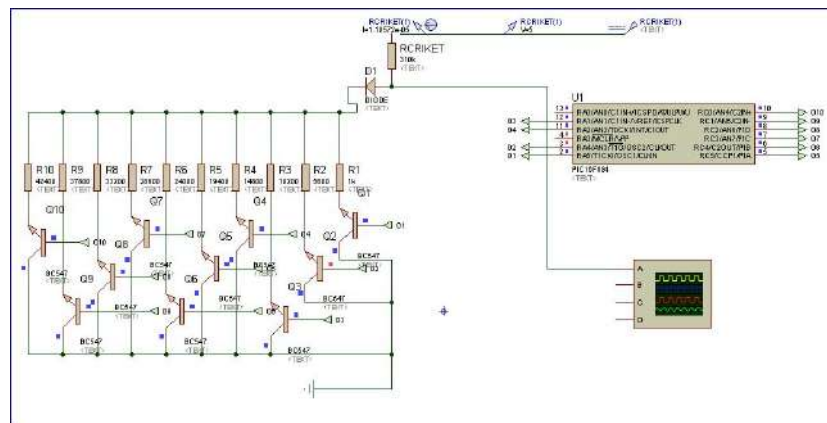


Figure 3.6: The electroshock delivery circuit.

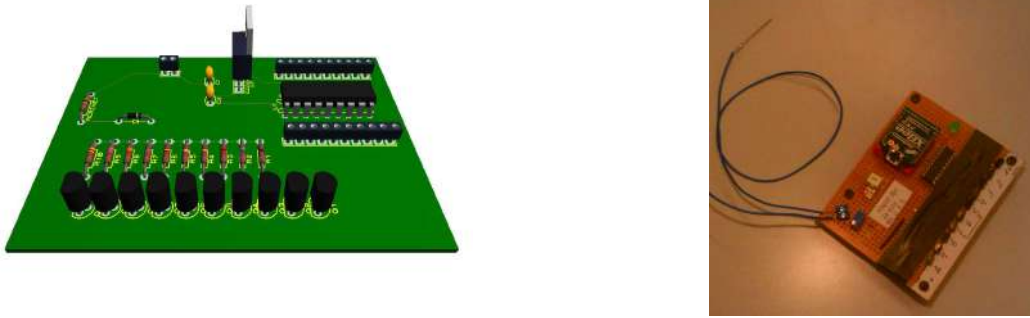


Figure 3.7: The electroshock delivery system circuitry model (Auto-Cad)(Left). The final electroshock delivery system (Right).

Serial-Bluetooth converter

In order to establish communication between cricket spacial position and orientation within the virtual environment and peripheral components (electroshock delivery mechanism and robot) we developed a Serial-to-Bluetooth converter (Figure 3.8). The circuit is assembled in a 6 cm x 4 cm circuit board where USB Remote Connector connects to a FT232BM333 chip (Future Technology Devices International Ltd.) which in turn directs the signal to a bluetooth transmitter (4214A-XBEE, MaxStreamTM).

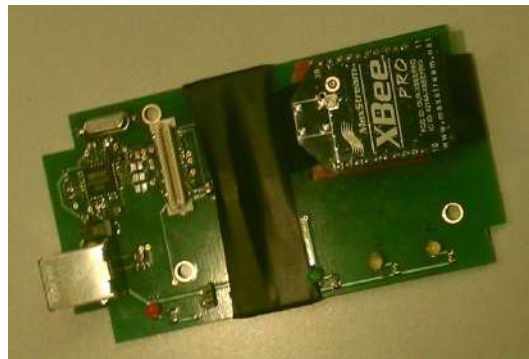


Figure 3.8: **Conversor** - communication processes from system server to mobile robot and electroshock delivery mechanism.

3.1.2 Software description

The InsectArcade system is composed by a nexus of connections among different applications on several computers. All computers are regular 32 bits machines running Ubuntu 11.04 (Linux) operative system. Figure 3.9 shows

the software architecture in terms of application connections. The main control (computer 1), runs the InsectArcade graphical interface where the whole system is set-up and the connections among applications are defined through the YARP middle-ware. Also, it runs the robot application that receives input from the virtual environment parameters in computer 2. The electroshock application was programmed using the C language and interfaces the virtual environment with the electroshock circuit through both YARP and serial communication processes. The Optical sensors application, also in computer 1, was developed using the C++ language and interfaces the optical sensor movements with the virtual environment movements through YARP. The real-time sound generated application was developed using the Pure-Data language and software, and interfaces the virtual environment position with sound parameters through the OpenSoundControl (OSC) framework (defined within the graphics application in computer 2 using the C++ language). Computer 2, 3, 4 and 5 are dedicated to graphics generation and all the applications were developed using the C++ language. Computer 2 sends feedback to the main control computer and controls the graphics generated by computer 3, 4, and 5.

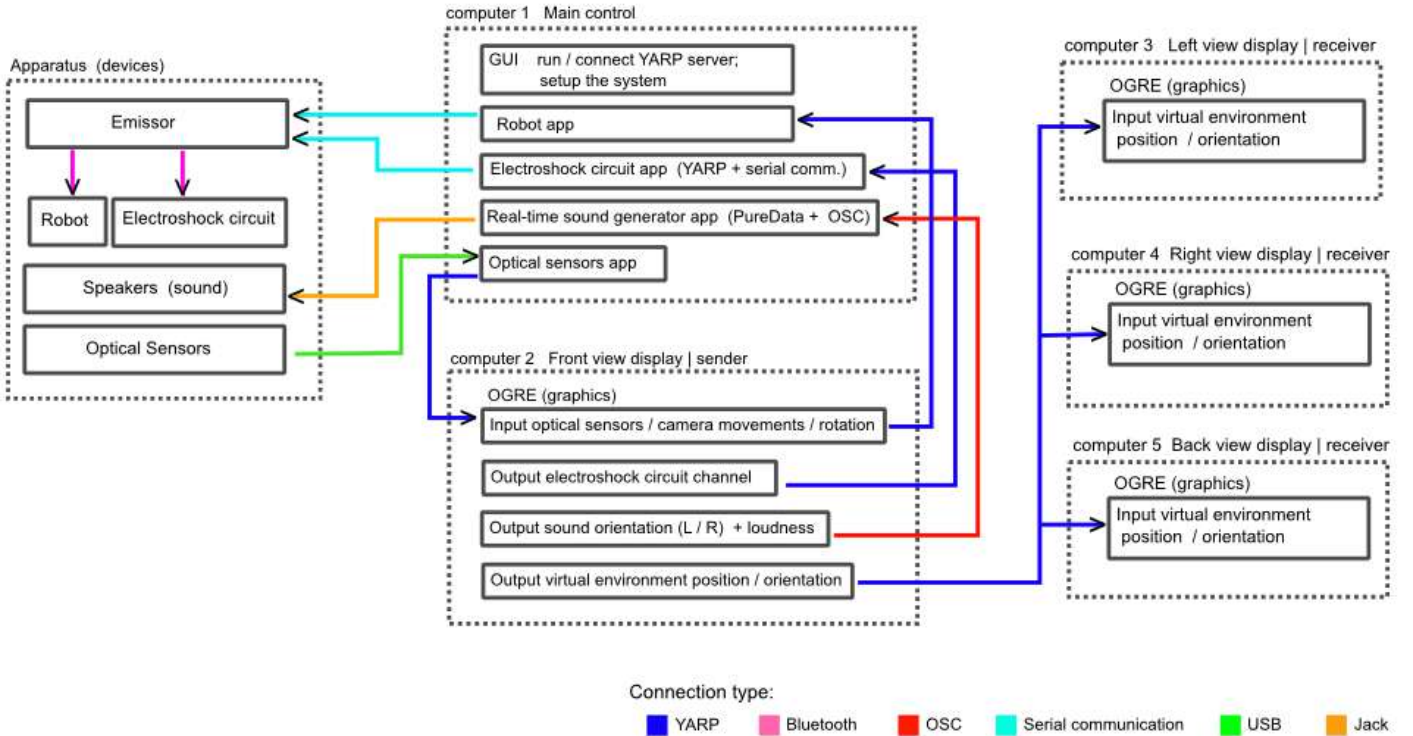


Figure 3.9: System software architecture

3.1.3 Auditory stimuli application

We developed a sound stimuli application capable of real-time sound generation (Figure 3.10). The presented sound architecture aims to mimic the male cricket (*Gryllus bimaculatus*) calling-song. Using the PureData framework, we achieved the species specific calling song of the *Gryllus bimaculatus* by generating an amplitude modulation of a 5100 Hz sound wave combined with an additive synthesis of 30 Hz phasor modulator. Both sound direction (left or right speaker) and volume are determined by the cricket position and orientation within the virtual environment. Figure 3.10 illustrates the sound application structure. The left column receives OSC package data, unpacks it, deals with sound volume, and outputs the sound direction parameter. The second column (in the middle), computes the speaker output. The right column generates the sound and converts it from digital to analogue signal.

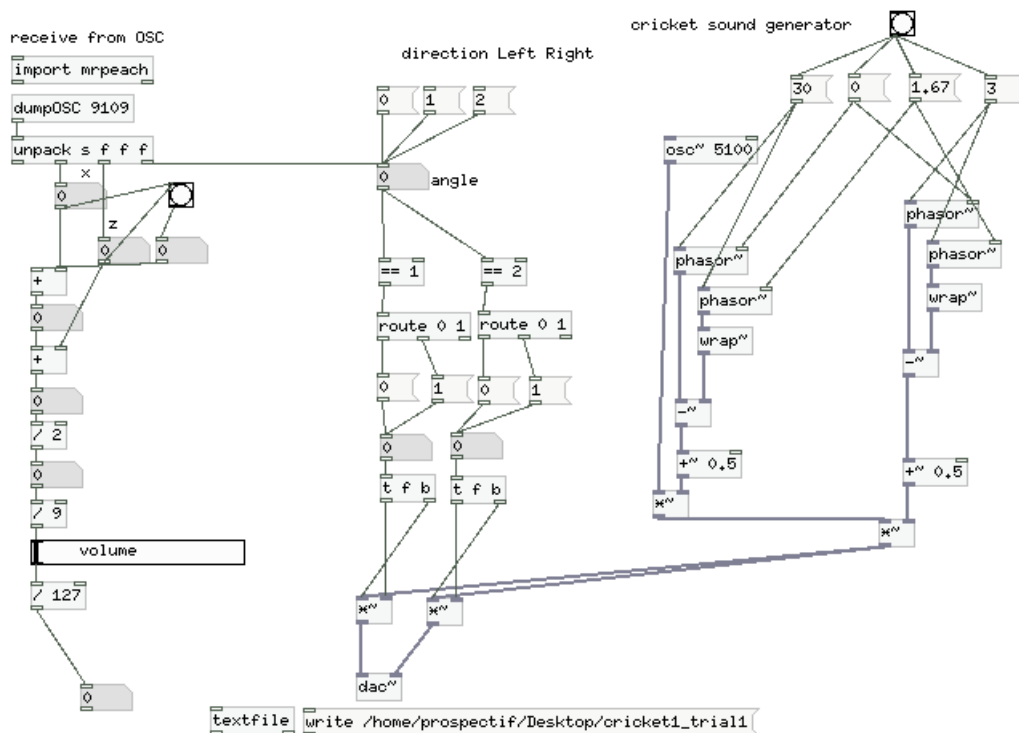


Figure 3.10: **Auditory stimuli application using the PureData software.** The column on the left receives input from virtual environment. Column in the middle computes the sound direction (left or right speaker). The column on the right, generates the artificial cricket sound.

3.1.4 Software usability

We developed a graphical user interface (GUI) that allows to set-up the whole system through only one computer. We used the Python programming language and the WxPython package to develop the interface. Controlling the whole system through only one computer is less time expensive when running experiments or setting up the system. By developing such interface we aim to facilitate the usage of the InsectArcade by other researchers. Figure 3.11 illustrates the GUI design. The InsectArcade 1.0 version GUI allows to define login file name, start or stop the sound application and start the virtual environment, or set-up the video tracking application for the mobile robot. It also checks, prints, and clean YARP ports for connections with system components, and allows to input new YARP ports and connect them.

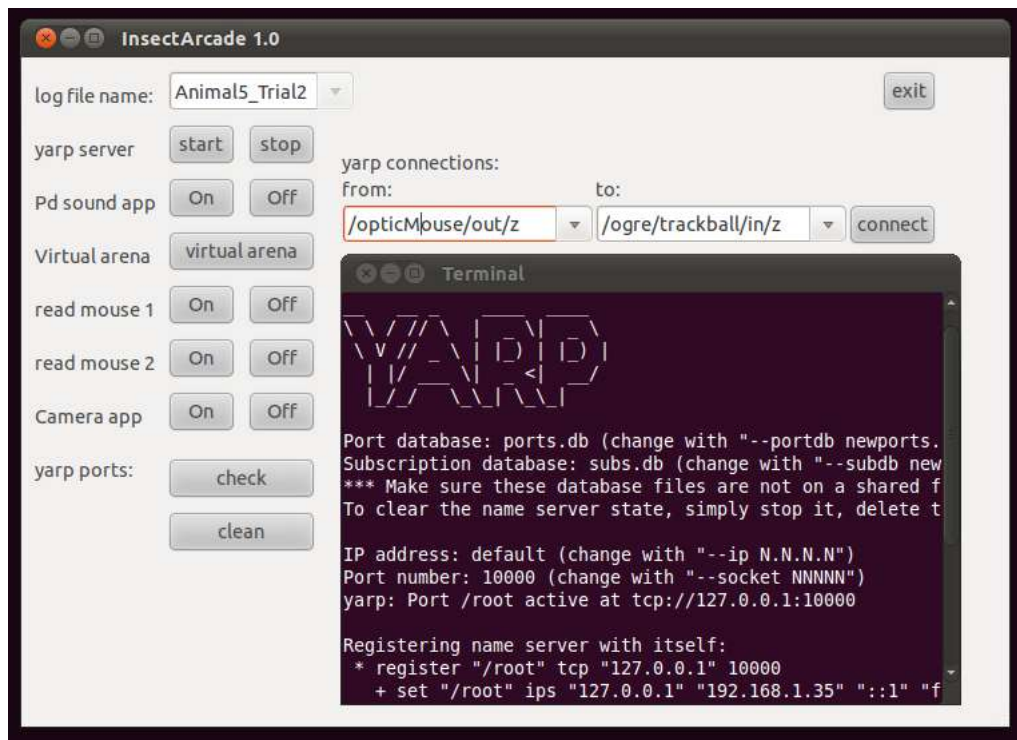


Figure 3.11: **InsectArcade graphical user interface.** InsectArcade graphical user interface with a regular linux terminal window on top. The left column defines login file name, system components states, and check and cleans YARP port connections. On the right side, new YARP port can be defined and connected. The regular linux terminal prints system states.

3.2 Validation experiments

To verify the system’s capabilities we performed a set of preliminary (system validation) experiments.

3.2.1 Antennae reaction to visual cues from the virtual environment

In a first system validation experiment, the animal was stimulated by exposure to the visual environment. We used ten adult female crickets *Gryllus Bimaculatus*, randomly chosen from a colony box of female crickets. All the animals were isolated and fed twenty-four hours before the experiment. To secure the animal to the apparatus, we attached a cotton-like bar to the prothorax of the insect. A completely dark virtual environment was designed, where only one red visual cue appear at time. We split the animals in two groups. In the first group, five animals were stimulated with static visual cues, appearing for three seconds in one of six possible positions, intercalated of 15 second between them. Visual cues positions were randomly defined but excluding the last presented position ($(pos = random(pos[1 : 6]) \& pos \neq pos - 1)$). Each animal was exposed to five sets of six positions. Three screens were used to stimulate the animal (front-screen, left-screen, right-screen). The positions were defined as: Front-close(F.C), displayed in the front-screen at 200 points in the virtual environment distance from the animal; Front-far(F.F.), displayed in the front-screen at 400 points distance; Left-close(L.C.), displayed in the left-screen at 200 points distance; Left-far(L.F.), displayed in the left-screen at 400 points distance; Right-close(R.C.), displayed in the right-screen at 200 points distance; Right-far(R.F.), displayed in the right-screen at 400 points distance.

We analysed animal antennae movement through direct (eye) observation each time the visual cue was presented. A boolean method was used to measure animal reaction to the stimuli. In case the antennas of the animal would not only react, but also point to the visual cue position, we would mark as *true* condition. In case the antennas were neither reacting or pointing to the stimuli position, we would mark as *false* condition. Data from all the animals of the first group was concatenated and both reaction mean and standard-deviation were computed.

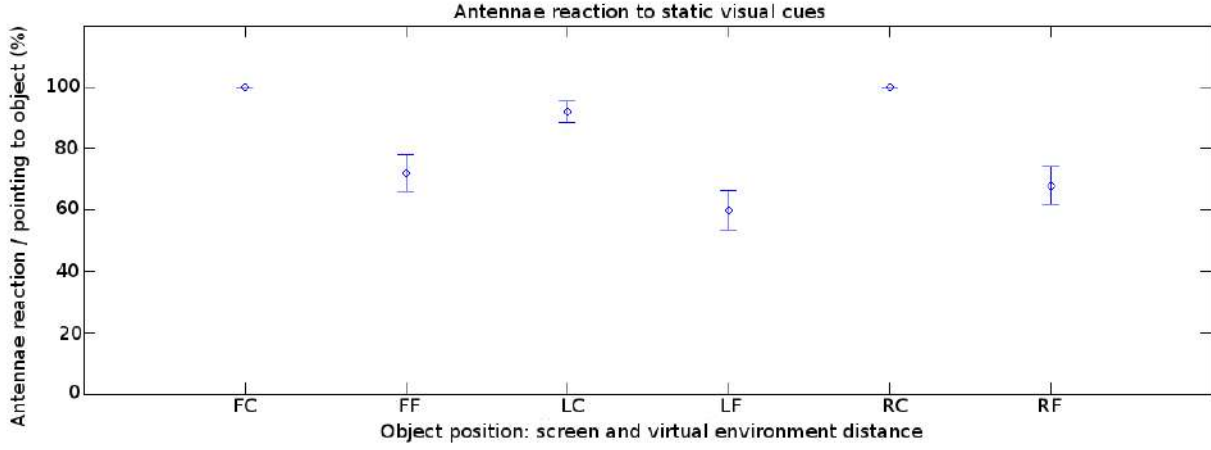


Figure 3.12: Mean and Standard-deviation of animal's antennae reaction to static visual cues.

In the second group, five animals were stimulated with dynamic visual cues, moving for 8 seconds in one of six possible axis, intercalated of 15 second between them. As before, three screens were used to stimulate the animal (front-screen, left-screen, right-screen). The axis were defined as: Front-close(F.C), displayed in the horizontal axis of the front-screen at 200 points in the virtual environment distance from the animal; Front-far(F.F.), displayed in the horizontal axis of the front-screen at 400 points distance; Left-close(L.C.), displayed in the horizontal axis of the left-screen at 200 points distance; Left-far(L.F.), displayed in the horizontal axis of the left-screen at 400 points distance; Right-close(R.C.), displayed in the horizontal axis of the right-screen at 200 points distance; Right-far(R.F.), displayed in the horizontal axis of the right-screen at 400 points distance.

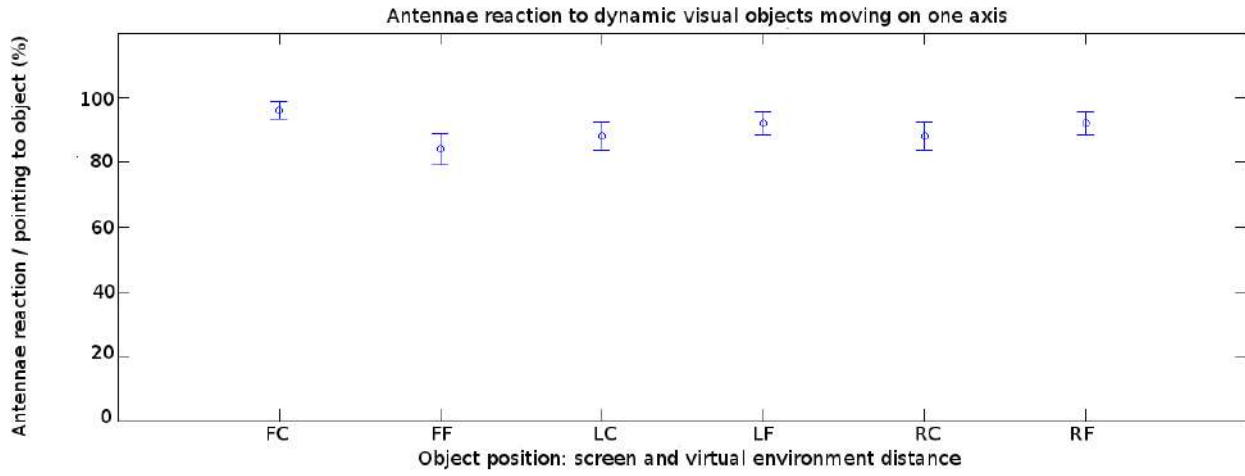


Figure 3.13: Mean and Standard-deviation of animal’s antennae reaction to dynamic visual cues.

3.2.2 Validating the system stimuli

In another system validation experiment, the animal was stimulated by exposure to the three different modalities of the system: visual environment, sound stimuli, and the electroshock delivery mechanism. We used one adult female cricket *Gryllus Bimaculatus*, randomly chosen from a colony box with both male and female crickets. The animal was isolated and fed twenty-four hours before the experiment. To secure the animal to the apparatus, we attached a cotton-like bar to the prothorax of the insect. A virtual arena was designed as shown in figure 3.14.

During the trial, a 4.8 kHz sound tone at a syllable rate of 1.67 Hz was generated in real-time to mimic the male cricket species-specific calling song. The selected speaker was defined by comparing the vectors between the “virtual sound source” and each one of the virtual cricket ears. Thus, the shortest

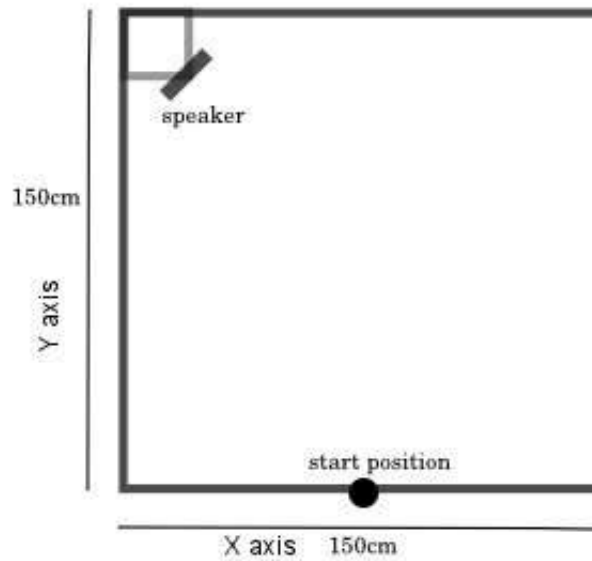


Figure 3.14: **Virtual arena description.** The insect starts at the "start position" ($x:75, y:0$). Sound and visual cue are in one of two positions: either ($x:0, y:150$), or ($x:150, y:150$).

vector (Left or Right) corresponds to the active speaker (Left or Right). The insect was placed on the top of the floating sphere. Two regular needles, connected to the electroshock circuit, were inserted into the cricket's abdomen. When the animal appeared to be quiet (around one minute later), the experiment started. Since the animal did not move during the first 19 seconds, a discharge of 0,005 Ampere (5V /1k) was delivered during one second. The electrical stimulation was not used again. The animal was able to reach the virtual sound source in four minutes and forty-five seconds (Figure 3.15 - Left). The extensively observed cricket Kramer treadmill walking pattern was also observed in our experiment. Figure 3.15 (Right), shows the trajectory of the animal and its dwell time at each position. Places where the cricket stopped for more than three seconds are represented by brighter dots. The mean speed was 53 cm/min while the max was 330 cm/min. The animal on the average stopped every 9.3 cm and stayed on the average 5 sec on these locations.

To analyse both the system's and the animal's performances, we ran one preliminary experiment. From the collected data we observed that the female cricket was able to navigate within a static virtual environment, moving towards the male cricket species-specific calling song when navigating on a floating sphere.

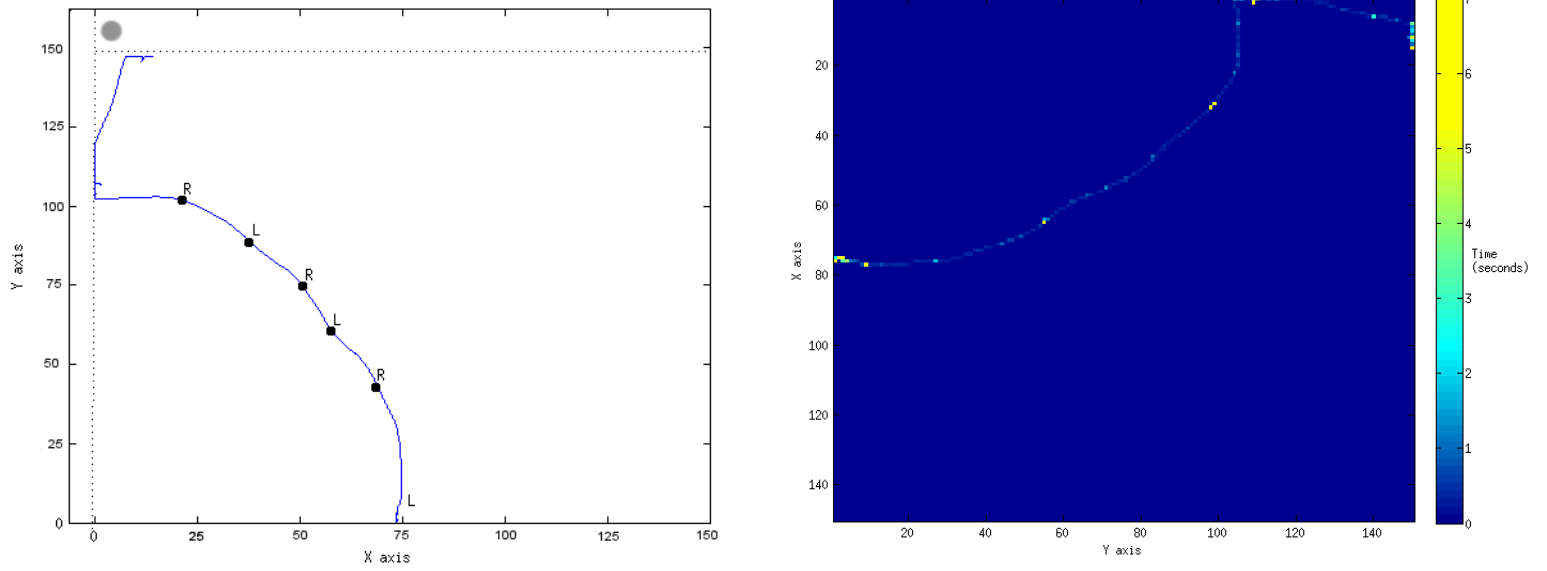


Figure 3.15: **On the left:** One trial with the 4.8 kHz sound tone at a syllable rate of 1.67 Hz. The sound stimulus direction is represented by L (left) and R (right) and only appears when the sound direction changes. Sound-source is represented by gray circle (upper-left corner). **On the right:** Heat plot: time at each position.

3.3 Cricket multimodal sensory integration.

To validate system accuracy and test animal behaviour consistency, we ran an experiment where each animal was stimulated by exposure to a dynamic visual environment and sound stimuli. We used twenty adult female crickets *Gryllus Bimaculatus* (ten each group), randomly chosen from a female colony box. Each animal was isolated and fed twenty-four hours before the experiment. To secure the animal to the apparatus, we attached a cotton-like bar to the prothorax of the insect. Each animal performed four navigation trials. During the first three trials, both stimuli were placed at the same position of the virtual environment (upper-left corner of the plots presented in Figure 3.20, 3.21, 3.22). In the last trial, the sound source changed to a novel position (upper-right corner of the plots presented in Figure 3.23).

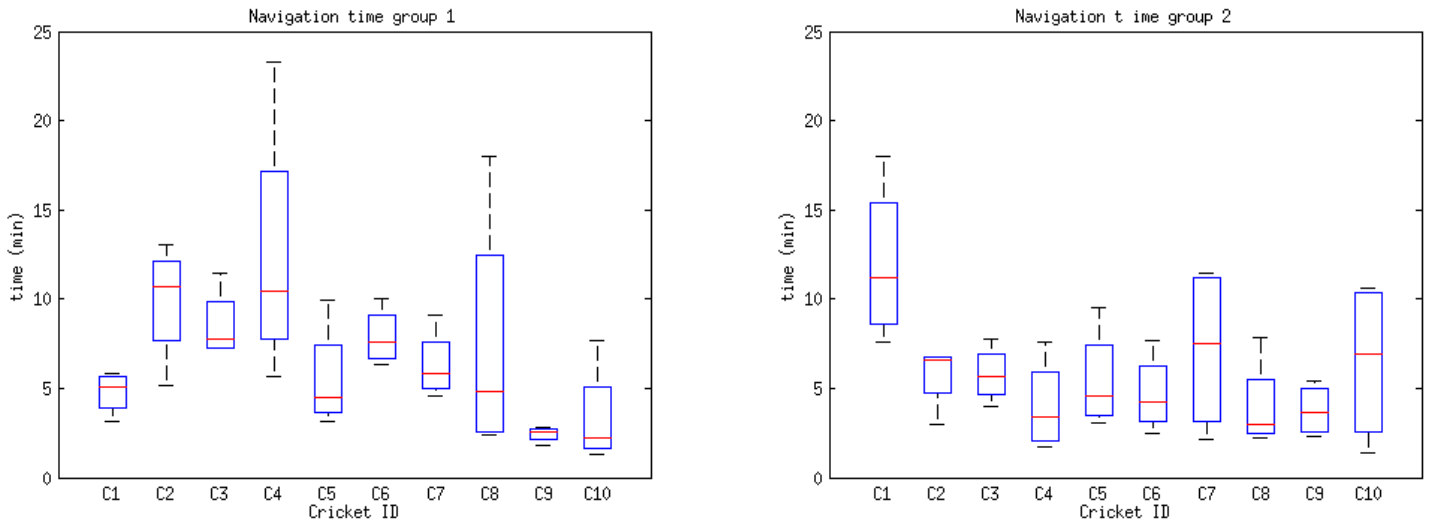


Figure 3.16: **Four trials each time variance.** Each bar-plot represents the time (in minutes) that each animal spent on navigating within the virtual environment. The mean time is represented by a red line, and the minimum and maximum time by the lowest and highest bar.

Trajectories by groups and trials

The plotted trajectories show the behaviour of all crickets of each group for each trial.

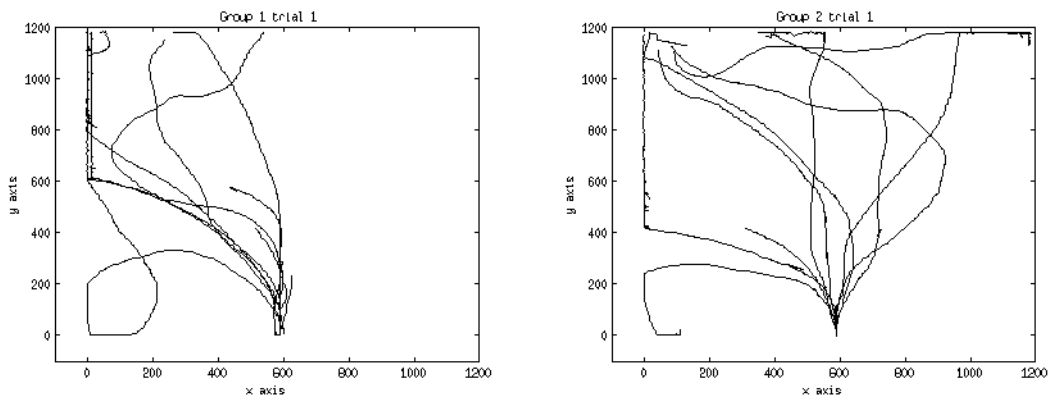


Figure 3.17: Trajectory of first trial, (Group 1, left; Group 2, right). Visual cue and sound source are placed on the upper-left corner.

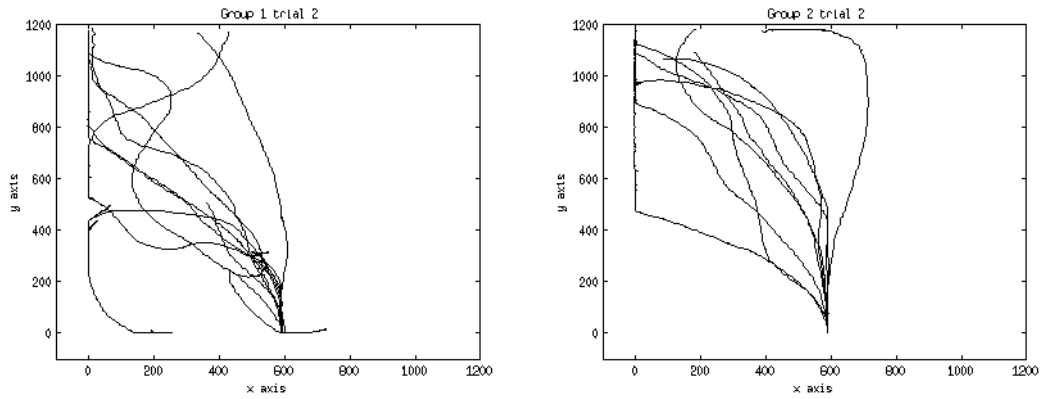


Figure 3.18: Trajectory of second trial, (Group 1, left; Group 2, right). Visual cue and sound source are placed on the upper-left corner.

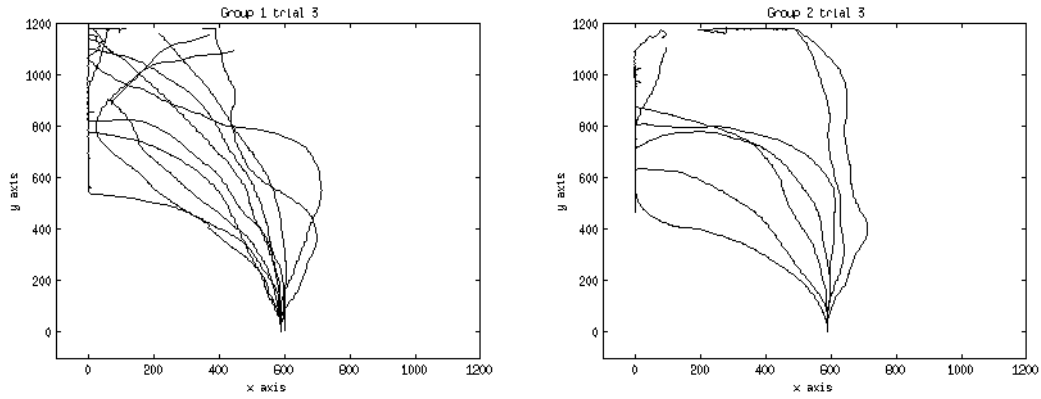


Figure 3.19: Trajectory of third trial, (Group 1, left; Group 2, right). Visual cue and sound source are placed on the upper-left corner.

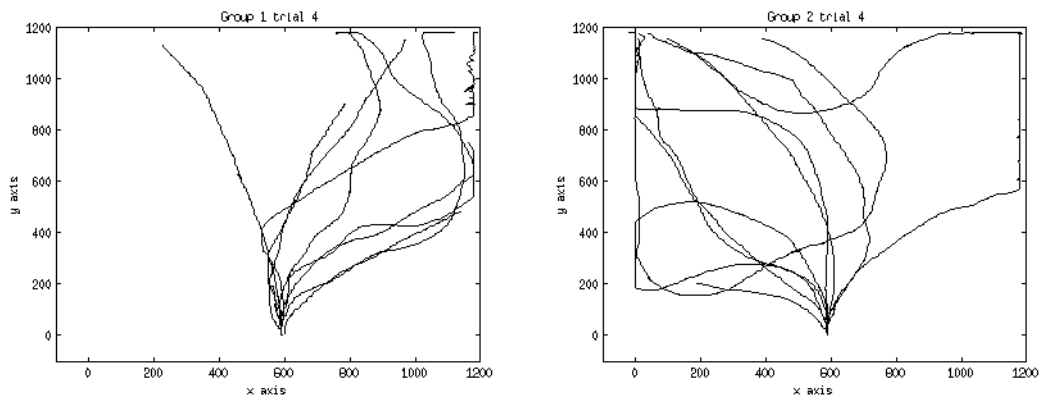


Figure 3.20: Trajectory of fourth trial. Group 1, left, changed the sound stimuli to upper-right corner. Group 2, right, changed the visual stimuli to upper-right corner.

The mean position of the x axis was computed to visualize animal position distribution on their last position. The results suggest that most of the animals prefer to walk towards the sound source position rather than the visual cue position. On the fourth trial of group 1, the sound source was changed to position 1000 on the x axis. On the fourth trial of group 2, the visual stimuli was changed to position 1000 on the x axis.

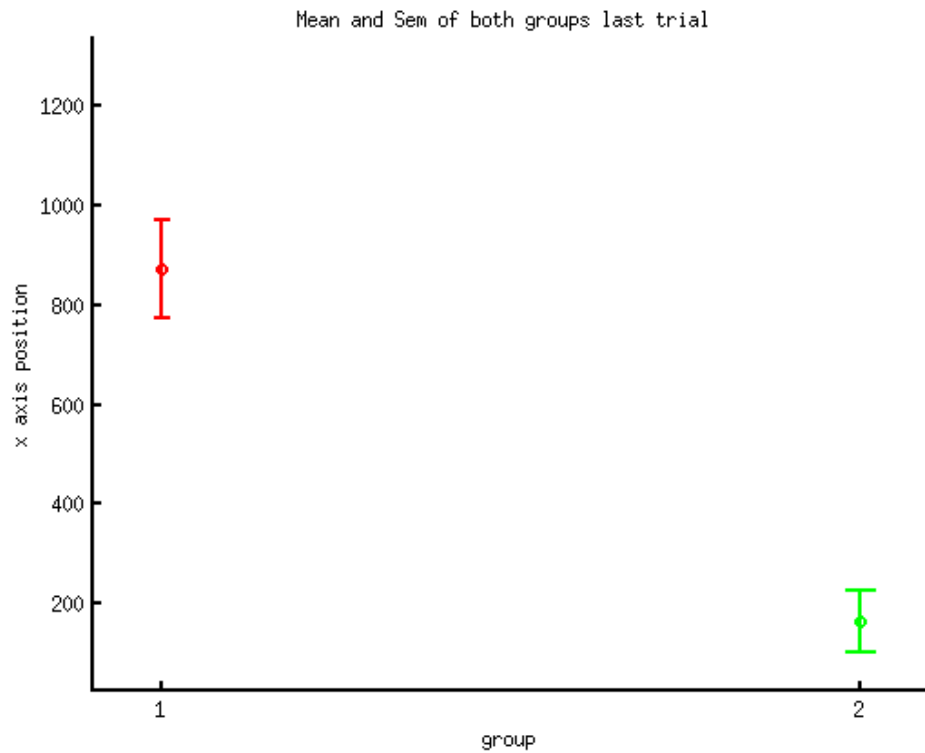


Figure 3.21: **Mean and Sem of both groups fourth trial final position.** The animals prefer to follow the sound source rather than visual cue.

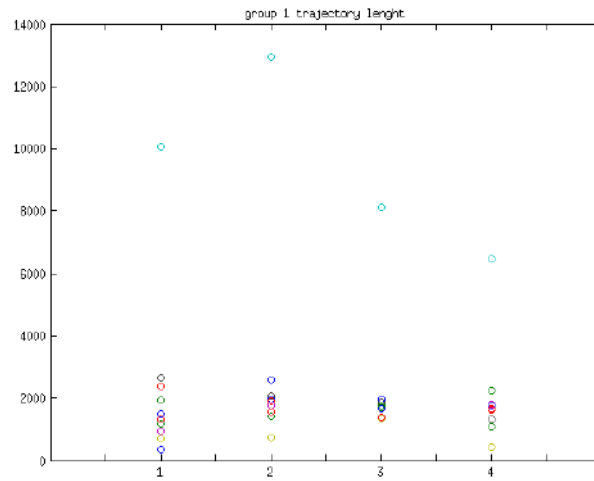
Animal trajectory length

Figure 3.22: **Trajectory length - group 1.** The trajectory length for each trial of each animal.

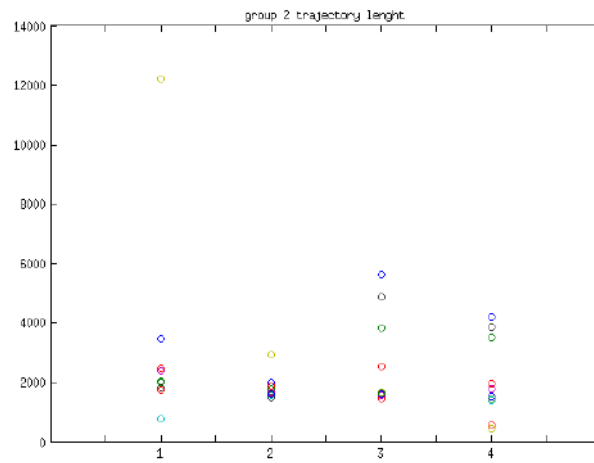


Figure 3.23: **Trajectory length - group 2.** The trajectory length for each trial of each animal.

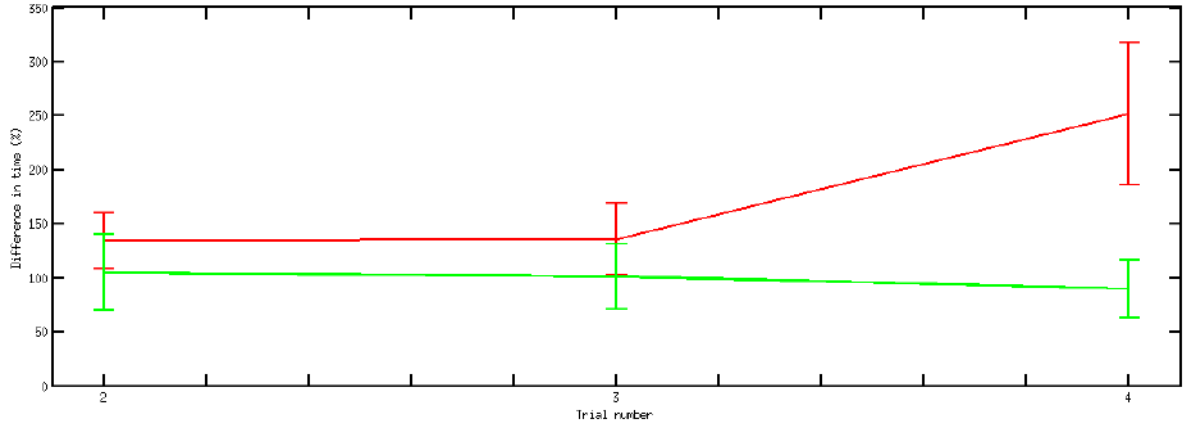


Figure 3.24: Differences in Time for both groups. Red line: Group 1 (sound moved to a novel position), Green line: Group 2 (visual cue moved to a novel position).

The time taken by individual female crickets to achieve the place-goal on the last trial of each experiment varied among our population. Since our experimental data is composed by non-parametric data, we used the Wilcoxon test to find significances in terms of spent time to arrive to the place-goal. Significances between the fourth trial of both groups were found with $p < 0.05$.

3.4 Insect controlled robot experiment

In this section we present preliminary results of the cricket controlled robot application. One adult female cricket (*Gryllus Bimaculatus*) was placed on the top of the treadmill compensator apparatus and immersed into a virtual environment. The visual feedback from the computer displays was the only sensory stimuli used in this experiment. The Insect-controlled-robot module of the InsectArcade system was used for testing the ability of the animal to control a robot and validate the mapping between the insect position within the virtual environment and the robot position within the real arena. Three trials of one female cricket navigating within the virtual environment and controlling the mobile robot on the real arena. The results suggest that the insect-controlled robot application can be used for hybrid tasks between the animal and a mobile robot.

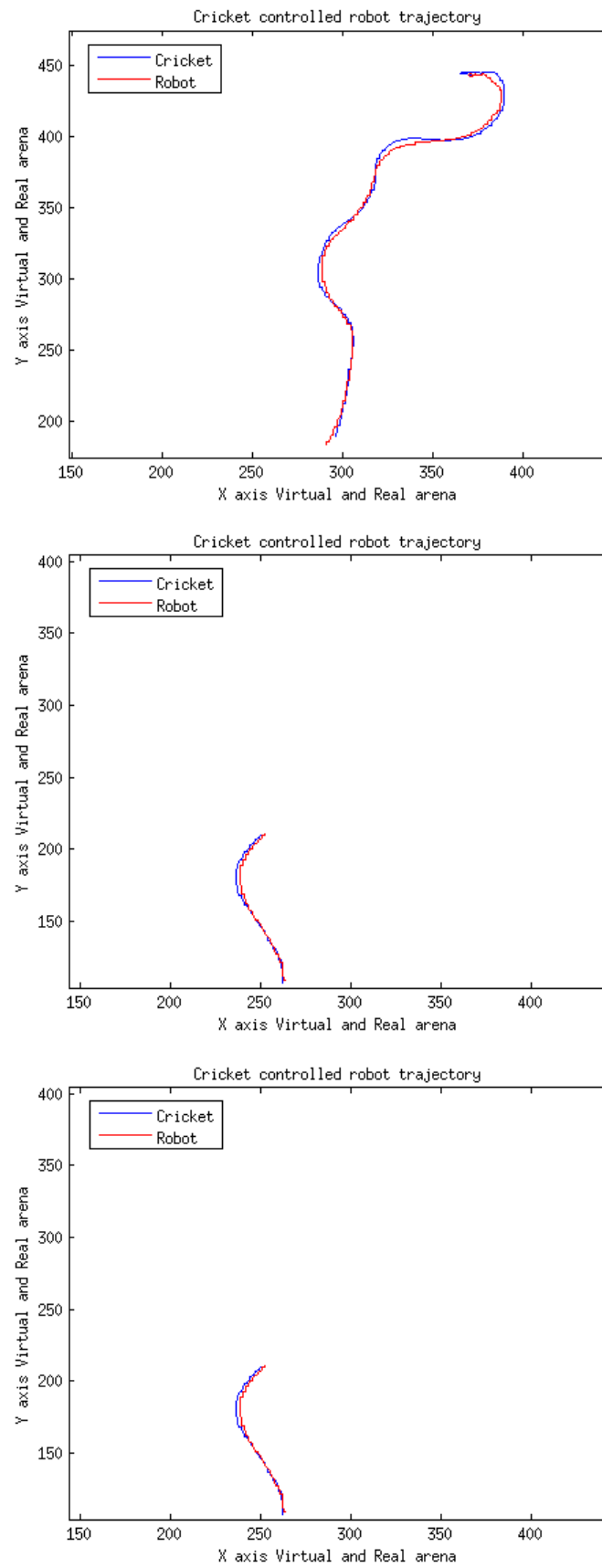


Figure 3.25: Cricket and Robot movements

Chapter 4

DISCUSSION

In this master thesis we have addressed the issue of testing the integration of multiple sensory modalities in insects through symbioses between biology, computational systems and mobile robots. We posed the question of what are the gains and priorities of both Auditory and visual modalities on the female cricket *Gryllus Bimaculatus*. We addressed this question on the development of insect-robot hybrid systems and in validation experiments with biological systems and mobile robots. Although insect multiple sensory modalities integration is optimally developed, robots are still lacking on efficient solutions to navigate within dynamic environments. One possible tool for the study of insect navigation and multimodal navigation, specifically for the study of gains and priorities of each sensory modality, are hybrid systems. Such systems allow the animal to behave symbiotically with computational architectures that synthesize sensory stimulation. In this thesis, we have presented InsectArcade, a novel mixed reality hybrid insect-robot experimental environment to study multi-sensor fusion and navigation in insects. The validation experiments results shown that our system is an accurate tool for the study of insect navigation. We have shown a set of experiments to validate the proposed system. The first experiment shows that crickets accurately point with their antennas to a visual cue presented in the virtual environment. We assume that the animal has, at least, a minimum of visual perception of the visual stimuli - computer display. In a second experiment, one female cricket performed a navigation task within the virtual environment towards a real-time synthesized sound source of her species-specific calling song. The animal was able to reach the desired position, which means that we were able to control the animal trajectory by sound stimulation. In a third experiment ten female crickets performed four navigation tasks each. During the first three trials both visual and auditory stimuli were placed in the same position. At the fourth trial, the sound stimuli changed to a novel position. In

the final experiment we set-up the insect controlled robot application and we tracked the behavior of both agents. The results showed that we are able to accurately control a mobile robot in a real arena accordingly with the insect navigation within a virtual environment.

We have shown that crickets can reliably navigate through a virtual environment that comprises visual and auditory stimulation. As we expected, moving the virtual visual cues to a novel position at the fourth navigation trial didn't affect the animal behavior as much as moving the sound source position. One reason could be that four trials were not enough for the animal to correlate both stimuli. In future work, we will increase the amount of trials until the animal is able to correlate both visual and auditory stimuli. With that, we aim to provide an insight on the gains and priorities of sensory-stimuli in such conditions.

References

- [1] H. B hm, K. Schildberger, and F. Huber, '*Visual and acoustic course control in the cricket gryllus bimaculatus*', J. Exp. Biol, 159:235248, 1991.
- [2] B. Brembs and J. Wiener, '*Context and occasion setting in drosophila visual learning*', Learn. Mem, 13:618628, 2006.
- [3] D. Dombeck, Khabbaz A., Collman F., Adelman T., and Tank D '*Imaging large- scale neural activity with cellular resolution in awake, mobile mice*', Neuron, 56:4357, 2007.
- [4] S. Emoto, N. Ando, H. Takahashi, and R. Kanzaki '*Insect-controlled robot evaluation of adaptation ability*', Journal of Robotics and Mechatronics, 19, 2007.
- [5] K. G. Gotz and C. Gambke. '*Zum bewegungssehen des mehlkafers tenebrio molitor*', kybernetik. Kybernetik, 4, 1968.
- [6] M. Mangan and B. Webb. '*Modelling place memory in crickets*', Biological Cybernetics, 101:07323, 2009.
- [7] Z. Mathews, S. Bermudez i Badia, and Verschure P.F.M.J '*An insect-based method for learning landmark reliability using expectation reinforcement in dynamic environments*', IEEE International Conference on Robotics and Automation, 2010.
- [8] Z. Mathews, M. Lenchon, J.M.B. Calvo, A. Dhir, A. Duff, S Bermudez I Badia, and P.F.M.J. Verschure '*Insect-like mapless navigation based on head direction cells and contextual learning using chemo-visual sensors*', Intelligent Robots and Systems, 194:7996, 2009.
- [9] G Metta, P Fitzpatrick, and L Natale '*Yarp: Yet another robot platform*', International Journal of Advanced Robotic Systems, 3:4348, 2006.

- [10] R. Okada, J. Ikeda, and M. Mizunami '*Sensory responses and movement-related activities in extrinsic neurons of the cockroach mushroom bodies*', Comparative Physiology A, 185:115129, 1999.
- [11] D. Shiramatsu, N. Ando, H. Takahashi, R. Kanzaki, S. Fujita, Y. Sano, and T. Andoh '*Target selection mechanism for collision-free navigation of robots based on antennal tracking strategies of crickets*', 3rd IEEE RAS and EMBS, 2010.
- [12] L. Verbugt, J. W. H. Ferguson, and T. Weber '*Phonotactic response of female crickets on the kramer treadmill: methodology, sensory and behavioural implications*', Journal of Comparative Physiology, 194:7996, 2008. .
- [13] R. Wehner, B. Michel, and P. Antonsen '*Visual navigation in insects: coupling of egocentric and geocentric information*', The Journal of Experimental Biology, 199:129140, 1996.
- [14] J Wessnitzer, A Asthenidis, G Petrou, and B Webb '*A cricket-controlled robot orienting towards a sound source*', Lecture Notes in Computer Science, 6856:112, 2011.
- [15] J. Wessnitzer and B. Webb '*Multimodal sensory integration in insects - towards insect brain control architectures*', Bioinspiration and Biomimetics, 1:6375, 2006.
- [16] A. Yamashita, N. Ando, Y. Sano, T. Andoh, H. Takahashi, and R. Kanzaki '*Closed-loop locomotion analyzer for investigating context-dependent collision avoidance systems in insects*', JRSJ Vol. 27 No.7, Sept., 2009.
- [17] M. Heisenberg '*What Do the Mushroom Bodies Do for the Insect Brain? An Introduction*', Learning and Memory 5:1-10, 1998.
- [18] F. Huber, T. E. Moore, and W. Loher '*Cricket Behavior and Neurobiology*', Cornell University Press, 1989.
- [19] Atkins, Gordon, Jason Kilmer, Michael Scalfani, Benjamin Navia, and John Stout '*Modulation of syllable period-selective phonotaxis by prothoracic neurons in crickets (Acheta domesticus): juvenile hormone, picrotoxin, and photoinactivation of the ON1 neurones*', Physiological Entomology 33 (2008): 322-333.
- [20] D. Otto and R. Campan. '*Descending interneurons from the cricket subesophageal ganglion*', Naturwissenschaften, Volume 65, Number 9 (1978), 491-493, DOI: 10.1007/BF00702845

- [21] H. Cruse . '*What mechanisms coordinate leg movement in walking arthropods?*', Trends in Neurosciences, 13:15-21, 1990.
- [22] P. Schaefer and R. Ritzmann . '*Descending influences on escape behavior and motor pattern in the cockroach*', Journal of Neurobiology, 49:9-28, 2001.
- [23] U. Bernardet, S. Bermdez i Badia, P.F.M.J. Verschure . '*A model for the neuronal substrate of dead reckoning and memory in arthropods: a comparative computational and behavioral study*', Theory Biosci. 127:163-175, 2008.
- [24] G. Jacobs and F. Theunissen . '*Functional organization of a neural map in the cricket cercal system*', Journal of Neuroscience, 16:769-784, 1996.
- [25] R. Brooks . '*Intelligence without representation.*', Artificial Intelligence, 47:139-159, 1991.
- [26] Barbara Webb . '*Using robots to model animals: a cricket test*', Robotics and Autonomous Systems 16:117-134, 1995.
- [27] A. G. Witney, and B. Hedwig. '*Kinematics of phonotactic steering in the walking cricket Gryllus bimaculatus (de Geer).*', The Journal of Experimental Biology 214:69-79, 2011.
- [28] J. F. A. Poulet, and B. Hedwig. '*Auditory orientation in crickets: Pattern recognition controls reactive steering.*', PNAS, vol.102, no.43, 15665-15669, 2005.
- [29] O. N. Larsen, A. Surlykke, and A. Michelson. '*Directionality of the cricket ear: A property of the tympanal membrane.*', Journal of Comparative Physiology, 153, 1983.
- [30] P. Boyd and B. Lewis. '*Peripheral auditory directionality in the cricket.*', Journal of Comparative Physiology A, 153:523-532 (1983).
- [31] Gerhardt HC, Huber F. '*Acoustic communication in insects and anurans: common problems and diverse solutions*', The University of Chicago Press, 2002.
- [32] Kramer E. '*The orientation of walking honeybees in odour fields with small concentration gradients*', Physiol Entomol, 1:27-37, 1976.
- [33] Poulet JFA, Hedwig B. '*Auditory orientation in crickets: pattern recognition controls reactive steering.* ', Proc Natl Acad Sci 102:15665-15669.