Paper: Rb34-1-11631; 2022/1/31

CameraRoach: A WiFi- and Camera-Enabled Cyborg Cockroach for Search and Rescue

Sriranjan Rasakatla*, Wataru Tenma*, Takeshi Suzuki*, Bipin Indurkhya, and Ikuo Mizuuchi***

*Tokyo University of Agriculture and Technology
2-24-16 Nakacho, Koganei, Tokyo 184-0012, Japan
E-mail: infibit@gmail.com, {s184300s@st.go, tszk@cc, mizuuchi@cc}.tuat.ac.jp
**Jagiellonian University
24 Gołębia, Kraków 31-007, Poland
E-mail: bipin@ugh.edu.pl
[Received May 15, 2021; accepted December 29, 2021]

We describe here our design and implementation of a cyborg insect, called CameraRoach, with onboard camera feedback that can be navigated via remote control providing a first-person view. The camera pack is mounted on the Madagascar hissing cockroach, which is small enough to fit into crevices but also can carry a printed circuit boards with power, communication, and sensor components (visual camera). For navigating the cockroach, we implemented a unique electronic backpack neural stimulator, which allows the cockroach to be maneuvered on a desired path with a joystick. A high-resolution wireless camera, also included in the backpack, sends live images via a WiFi (Wireless Fidelity) network. We present the results of an evaluation experiment with the CameraRoach and compare it with the other state of the art systems like the Beetle-Cam.

Keywords: cyborg insect, search and rescue, bio-bot, neural stimulation

1. Motivation and Background

Our goal is to develop a camera-based cyborg insect for search and rescue. It should be possible to control the insect to navigate it through a disaster site, and one should be able to receive live camera feedback from the insect. Past research has explored many techniques for neural stimulation of insects to control their movements, and other research studies for receiving live audio or video feedback from the insect's surroundings [1, 2], but there has not been research on the combined ability of exploration with a camera with neural stimulation for gait control. One recent such system developed by Iyer et al. [1], which we will refer to as Beetle-Cam (Beetle camera), uses a low-resolution camera mounted on a beetle to send live images via Bluetooth. However, it does not have any mechanism to guide the beetle on a desired path. If we were to use a cyborg insect for search-and-rescue, or for inspection, then we need live camera feedback and an ability to navigate the insect.

In the research described here, we remedy this situation by implementing a cyborg insect mounted with onboard camera feedback, which can be navigated via neural stimulation. We chose the Madagascar hissing cockroach (*Gromphadorhina portentosa*) as the insect to mount the camera pack. This cockroach is not only small enough to fit into crevices but also can carry a printed circuit board with power, communication, and sensor components. For navigating the cockroach, we implemented a unique electronic backpack neural stimulator, which allows the cockroach to be navigated on a desired path with a joystick. A high-resolution wireless camera, also included in the backpack, sends live images via a WiFi (Wireless Fidelity) network. Our system, which we refer to as CameraRoach, is a significant improvement over Beetle-Cam [1], and a detailed comparison is presented at the end of this paper. For search and rescue in a disaster situation, it is very crucial to get information about where the injured people are, and who is alive and who is not. This allows the rescue team to concentrate their efforts to reach people for whom timely assistance is crucial. For this task, robots, especially microrobots, can be very useful, and a number of such robotic systems have been designed [3, a]. However, another approach is to use insects that can be remotely manipulated to control their movement [4, 5], and can send back live video or audio feedback of their surroundings. Insects have naturally evolved to move around in a wide variety of terrains using different modes of locomotion [6]. They provide an interesting mobile platform for attaching a neuro-stimulator probe and a miniature camera or microphone. These probes, sensors, a battery, and a communication device (like Bluetooth) are usually put on an ultra-lightweight backpack that is mounted on an insect [7]. We refer to such a backpack-mounted system as a *cyborg insect*, which one day can be maneuvered through the rubble and debris using its natural locomotion to find out the locations of injured people. There is already some research on developing cyborg insects, and we briefly mention some such systems here.

Whitmire et al. [2] developed a system based on an omnidirectional microphone to listen to help calls from victims trapped under the debris, find their location by tracking the source of the sound, and establish contact with the first responders. The microphone and an RF (radio frequency) link were integrated in a backpack, which could be mounted on a small robotic insect. They also tested their system by mounting it on a Madagascar hissing cockroach, where the estimated direction of the sound source was used to steer the cockroach through electroneural stimulation (a set of five 30 ms pulses given every 400 ms). However, in this sound-based approach, the cockroach cannot always localize because there is no line of sight and there are obstacles. In later works [8, 9], they implemented a Kinect camera-based automatic tracking and steering of cockroach bio-bots. However, an external camera is not so effective for search-and-rescue, and an onboard camera is needed.

Latif et al. [10] describe a fenceless boundary system which keeps the bio-bot nodes within a charging distance range of a base station. They used a solar panel-based charging system with an RF (radio frequency) link in the battery backpack of the cyborg insect cockroach. When stimulating the cockroach along a path, it was observed that a shorter but more frequent pulsing allowed a more precise navigation control of the cockroach. They also observed that simultaneous stimulation of both antennae made the cockroach perceive an immediate obstacle in front of it due to that it would stop for 0.5–1 s and then continue its motion. These observations are incorporated in our design of CameraRoach. However, in their system, they use the RF signal strength [11] to get information about the surroundings of the cockroach, whereas we deploy a camera to get a visual image.

Faulkner and Dutta [12] present a number of useful observations and guidelines for controlling an insect through neuro-stimulation. They found a 1.2 V signal at 55 Hz frequency at 50% duty cycle to be most effective for evoking a robust response from the cockroach. To make a right turn a stimulus of the PWM signal is applied in the left antenna and vice versa. It was also observed that the response of the insect decreases when the same stimulus is applied several times. Alternating the pulse stimuli invokes a better steering control of the insect. For example, applying a stimulus to the left antenna, then a short stimulus to the right, followed by a major stimulus to the left, keeps the right turning response strong; the insect does not become numb to repeated stimuli.

Dirafzoon et al. [11, 13] describe a stimulation technique for making a cockroach move continuously. Hissing cockroaches were used with four electrodes implanted in their body. One electrode each was inserted in the two antennae, a third into the cercus and the fourth ground electrode into the mesothorax. Stimulation in the cercus makes the cockroach move forward whereas the antenna stimulation steers the cockroach left or right. We adopted the same approach in CameraRoach.

In an early work, Bozkurt et al. [14] presented a simulation of RF-based cyborg insects known as biobots with minimal sensing capabilities and localization constraints to map an unknown environment for emergency response situations. Robust topological features are identified in the formed maps in simulation. In our work, the scene around the immediate environment of the cyborg insect is transmitted via a camera. Bozkurt et al. [14] also use omnidirectional and unidirectional microphones to help locate survivors by listening to their help cries. Microphones were used on a cockroach in its neural stimulation backpack for locating a sound source and making the cockroach move towards it. All this was done in a simulation. However, a problem with sound localization is that it works only within the line-of-sight and does not if there are obstacles. Our system CameraRoach is better because using a camera one can gain an immediate knowledge of the surroundings and take the decision to move. Tran-Ngoc et al. [15] described a new embedded electronic backpack for the cyborg cockroach, which has a thermal camera and a GPS chipset. The problem with only using a thermal camera is that the features in the thermal image are not sufficient for navigation. Our visual wavelength camera has given the cockroach the ability to scout for objects of interest like survivors through the combined ability of neural stimulation. **Table 1** summarizes the work of several researchers on cyborg insects.

The main contributions of this paper are as follows. This is the first cyborg insect system that can be used for inspection/exploration with a first-person view from a camera for search and rescue scenarios. Our system has a high-definition camera and can be operated remotely by looking at the live visual feedback coming from the insect. It is typical to find WiFi coverage in cities, university campuses, and office campuses rather than find Bluetooth network coverage. So, using WiFi in urban search and rescue scenario makes more practical sense.

The major difference compared to [1, 15] is that this is the first time a first-person view navigation system has been developed on a cyborg insect. In paper [15] only external navigation (not first-person view) has been implemented. Reference [1] shows a small camera being integrated on a beetle insect but if one has to perform the process of search, we feel that first person view navigation with controlled and guided motion of the cyborg insect is necessary. A controlled motion or guided navigation is not possible in Beetle-Cam because neural stimulation like in a cockroach is not possible in beetle insect yet thus using Beetle-Cam we cannot do first person navigation. We developed our own daughter board hardware to combine a miniature camera with high resolution, frame rate, and neural stimulation control into a single platform. This was quite an engineering challenge to combine both WiFi technology onto a board that is small and lightweight enough such that it could be carried by an insect. We practically achieved large field of view of about 1600×1200 pixels, colored image transmission, with a low latency control of about 90 ms because we were able to send about 10 packets of navigation data or more in about 1 s. The situational awareness

Table 1. Various cyborg insect backpacks with specifications.

No.	Cyborg insect backpack specifications			
	Author	***Insect platform***	***Payload specifications***	***Purpose***
1	Whitemire et al. (2013)	Gromphadorhina portentosa	PIC16F687, IA4220 RF link	Kinect based tracking and control
2	Whitmire et al. (2014)	Gromphadorhina portentosa	Unidirectional and omnidirectional mics	Microphone based search and rescue
3	T. Latif et al.	Gromphadorhina portentosa	Solar powered mobile RF link	Fenceless boundary system
4	H. Sato (2008)	Cotinis texana beetle	TI MSP430	Insect flight control system
5	H. Sato et al. (2009)	Mecynorhina beetle	CC2431 RF chip	
6	Faulkner	Cockroach	SAMB11-ZR chip	Cockroach gait control
7	Dirafzoon et al.	Periplaneta americana	RF transceiver	Mapping
8	Bozkurt et al.	Manduca sexta moth	Atmel ATTINY13V	EMIT based moth flight control
9	Cole et al.	Gromphadorhina portentosa	CC2530, gyro, and IMU	Motion mode identification
10	Schwefel et al.	Blaberus dicoidalis	Low voltage oscillator	Implanted fuel cell
11	Iyer et al.	Eleodes nigrina (beetle)	Bluetooth vision sensor	Insect scale vision

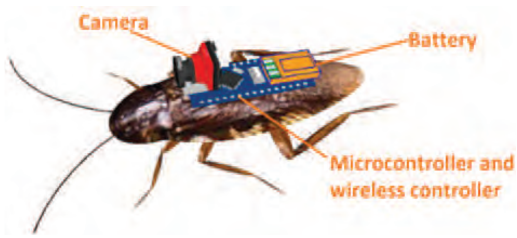

Fig. 1. CAD model of the camera roach system.

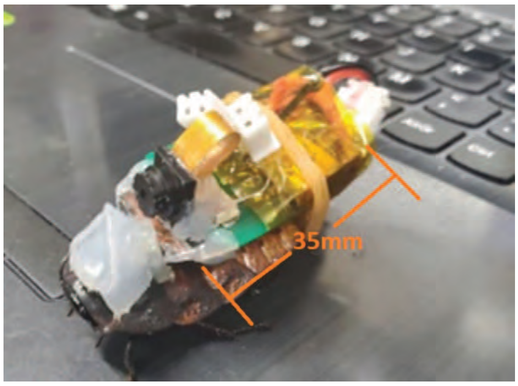

Fig. 2. Cockroach with WiFi control board and camera (brown colored cockroach body beneath the green PCB, size shown).

improves with a high-resolution image/video from the on-board cockroach camera and one can also pan to change view with the lowest stimulation PWM signal. For example, if we can improve the process of search, then the time to search for survivors will come down, help for survivors can come faster, and more people can be saved. And we believe that for improving this process of search our research through the CameraRoach system would add value. The time to search for an injured survivor is of utmost importance in a search and rescue scenario and we need to reduce this as much as possible and in such cases a higher frame rate and higher resolution provided by WiFi are necessary than when compared to Bluetooth.

The rest of the paper is organized as follows. We describe here the design and implementation of our CameraRoach system (Section 2), followed by the evaluation experiments and a comparison of our system with the existing systems (Section 3). The conclusions and suggestions for future research are presented in Section 4.

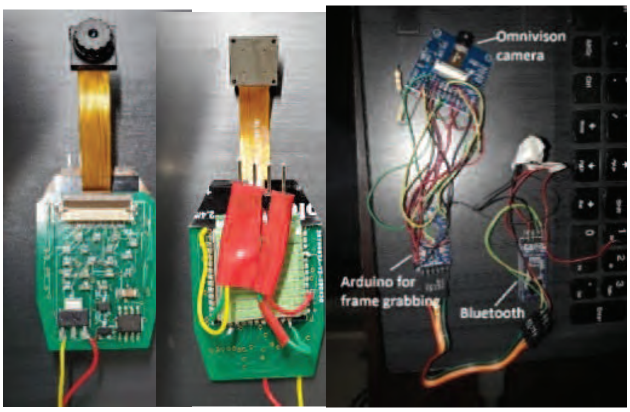

Fig. 3. (Left) WiFi camera hardware. (Right) Bluetooth camera hardware.

2. Implementation of the CameraRoach

We describe here the surgical procedure, the embedded hardware, and the software architecture of the CameraRoach (**Figs. 1** and **2**).

2.1. Embedded Systems

We built and tested several versions of wireless camera hardware in this research. First, we tried Bluetooth (**Fig. 3**, right), but the camera was too bulky, the frame rate was limited by the bandwidth, and the frame data was error prone and not so reliable. One primary reason why our work on Bluetooth boards was abandoned was because of low frame rate and low resolution of the image. First person view navigation needs better frame rate at a higher resolution, and the frames that are not

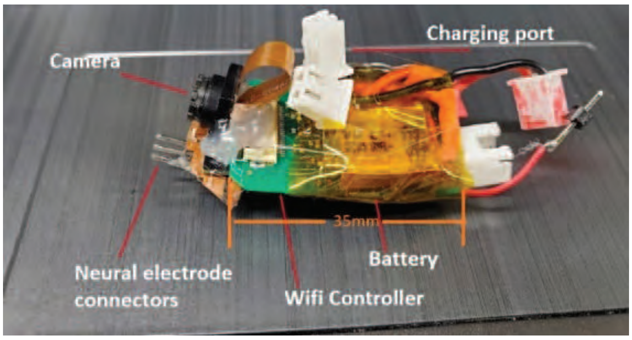

Fig. 4. WiFi neural controller backpack with camera (scale bar shown).

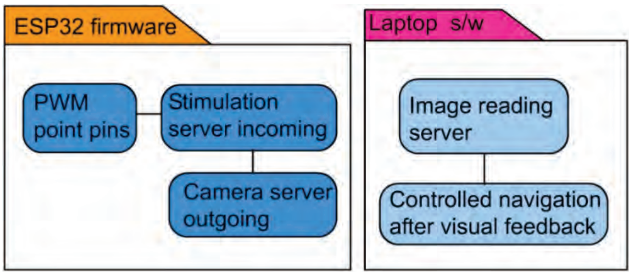

Fig. 5. Software server architecture.

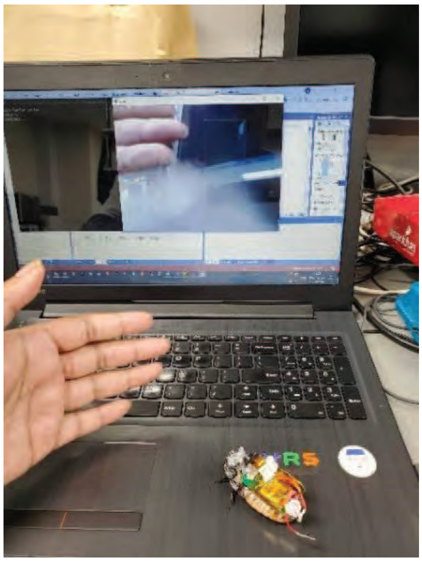

Fig. 6. A still of the live video feedback from CameraRoach. The camera is placed on the head of the cockroach, which is looking towards the hand of a person, and this feedback is relayed over WiFi to the laptop.

prone to error. Therefore, we switched our efforts to WiFi based daughter boards (**Fig. 4**). One advantage with WiFi is that in a university campus where there is already an established WiFi spreading across the entire geographical area we can actually realize Bozkurt's cockroach network model in practicality. So, we chose to use the ESP32 WiFi SOC, which is connected to an omnivision camera and sends images over WiFi (**Fig. 3**, left and **Fig. 4**). The system is powered by an onboard 7.4 V, 125 mAh Li-Ion regulated power supply for both the WiFi SOC and the camera. The ESP32 daughter board was custom designed for this project. PWM control signals are provided on individual ports. There is a provision for Flash LED for frame grabbing and video under low light conditions. Our board is the smallest breakout board for the ESP32 compared to its commercially available versions. We have provision for both PCB antenna and an external antenna with a UFL connector. The frame rate is better with an external UFL antenna. We used a flexible PCB UFL antenna as well.

After conducting several cockroach surgeries, we observed that one needs to be extremely careful of the electrode tissue bonding, which was different for different trials. We had to calibrate our system individually to each cockroach to yield a better neural stimulation response. Depending on the depth of insertion of the electrodes in the antenna and the tissue electrode bonding after the cockroach recovers from the surgery, the stimulation response was different. So, we had to test for pulse widths ranging from 1 ms to 20 ms to see how well the cockroach would respond. In some cases, the cockroach did not respond at all, indicating a failure in the surgery, some cockroaches had a good turning response for 4 ms pulses, in some cases it had to increase to 10 ms or 20 ms and even if turning in one direction would be successful the other direction it would be weak or none at all in which cases surgery was performed again on fresh cockroaches and then tested for turning response.

We found that a 50–60 mAh battery pack lasts only six minutes because WiFi consumes more power than the Bluetooth radio. To improve this, we used a LiPo DC-DC boost converter, which gave us a battery run time of 30 minutes or more using a single 125 mAh battery. The CameraRoach system that has a single ESP32 wrover module made by Espressif systems, manufactured in China, consumes between 80 mA to 260 mA, running at 3.3 V, OV2640 that is the omnivision camera sensor, also manufactured in China, consumes 125 mW maximum power at 1.2 V to 3.3 V.

2.2. Software Architecture

The camera uses our custom-developed firmware (**Fig. 5**) running on the ESP32 SOC, which connects to a WiFi network and sends image data over a port with an IP (internet protocol) address. The neural stimulation signals for the cockroach are sent over another port on the same IP. We can set the image resolution up to a maximum of 2048×1536. We can also adjust the gain, exposure control, and automatic white-band equalization. On the laptop end, the images can be read on any browser **(Fig. 6)**, but we have developed code to access the images using Libcurl software library. The stimulation commands are sent to the cockroach controller from the laptop (**Fig. 7**) over WiFi using Libcurl. The stimulation signals are controlled by a joystick connected to an Arduino. If there is WiFi coverage in the area of operation, the cockroach

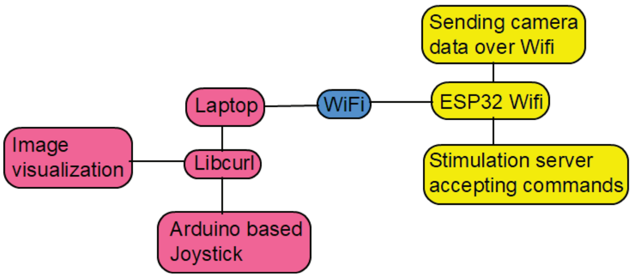

Fig. 7. Hardware and software layout of CameraRoach. Yellow color indicates ESP32 side system, laptop side system is indicated in pink and the connecting WiFi bridge is indicated in blue.

camera can send signals without any range limitation. In the software architecture there is firmware running on the ESP32 micro-controller and there is laptop end software. The ESP32 firmware has PWM stimulation routines running which is available as a webservice over an IP and there is camera image streaming server routine running. At the laptop side there is image reading client and navigation control client routines running which accept command over USB RS232 port to accept the joystick commands and map them onto the IP based stimulation routines. **Fig. 7** shows the hardware and software schema block diagram. The laptop and the cyborg cockroach microcontroller are connected over WiFi. On the laptop end, the software is based around Libcurl. Libcurl's IP based commands are mapped with Arduino joystick routines to send stimulation commands and there is image reading client which uses Libcurl to read the images over an IP address. There is some serial-port code running on the laptop, which handles the USB to serial communication with the Arduino that is attached to a joystick shield.

2.3. Surgical Procedure

We used mature female Madagascar hissing cockroaches in this project. Each surgery was performed under a microscope by first anesthetizing the cockroach with CO_2 gas. The cockroach would wake multiple times as the effect of CO_2 anesthetization would wear off. CO_2 anesthetization is much comfortable and faster compared to other approaches like anesthetizing the cockroach by keeping it in ice or in the refrigerator. As per our experience a typical session of cockroach surgery would take 40 min to 1 h. So when anesthetizing by ice we found it would take longer for the cockroach to go to sleep and when it wakes up again the procedure for anesthetizing it would have to be repeated again. Ice based anesthetizing would put the cockroach to sleep in 10–15 min whereas CO_2 would put to sleep it under 1 min. The waking up times from both CO_2 and ice are almost the same which is around 10 min. So, CO_2 helped reducing the surgery time and was more convenient.

We used platinum-iridium (90% platinum, 10% iridium) wires from the manufacturer A-M systems as the electrodes to stimulate the cockroach. The wires had a bare diameter 76.2 μm and a coated diameter of 139.7 μm. The insulation had to be burnt off and the wire tip neatly cut before inserting it into the antenna and cerci. Four electrodes [b] were inserted: one in each of the two antennae, one in thorax, and one in cerci. We made berg strip female connectors and glued them to the cockroach body on the head and at the lower part of its body. The success rate of our surgery was that one out of every three cockroaches responded successfully to both the antenna and the cerci stimulation.

The stimulation was done using a pulse-width modulated (PWM) signal of adjustable duration and frequency. Stimulating cerci induces forward motion. If we stimulate both the antenna, then the cockroach stops. If we supply a PWM signal to the thorax and treat the antenna as the ground, then the cockroach moves back. Stimulating the left antenna makes the cockroach turn right, and stimulating the right antenna makes the cockroach turn left. Some useful tips we learnt from our experience are: 1) Keep the cockroach in a terrarium with no wood chips so that nothing gets stuck to the antenna electrodes to avoid having them ripped off. 2) Hold the antenna backward with glue. 3) It is useful to burn the electrode silver wires about 3–4 mm to remove the insulation and clean it with alcohol before implanting to ensure that it is free of insulation material, glue and grease.

3. Results

3.1. Evaluation Experiments

We have seen different form of stimulation profiles and systems. Some use light from LEDs to stimulate the optic lobes of the insect's brain like this paper here. Sato et al. [4] and some techniques involved early metamorphic insertion of electrodes in the pupilar stage of an insect (Bozkurt et al. [16]). The work of Latif et al. [10] demonstrates gait control of a cockroach through antenna and cerci stimulation through electrodes, which is better suited for directional control of a cockroach and maze-like experiments.

We conducted a number of experiments to evaluate the capabilities of CameraRoach, including its ability to be navigated through a maze and send back live camera feedback. A demo video of CameraRoach can be seen here [c, d]. The cockroach with the given payload of 11.2 g is able to climb over small obstacles like pebble stones (**Fig. 8**, right), though the payload reduces its speed and stability; if it tilts beyond a point to either side it tends to flip over. In the future designs, we aim to further reduce the weight of the WiFi camera and the neural controller. Sometimes on smooth floor with heavy payload like in a smooth plastic box the cockroach seems to slip, when we tested the cockroach in its natural environment like on sand and mud in a box it was able to carry a heavier payload of 16 g with ease. The problem is the center of gravity. The cockroach's body is pretty light (about 22 g), and the payload moves its center of gravity up and

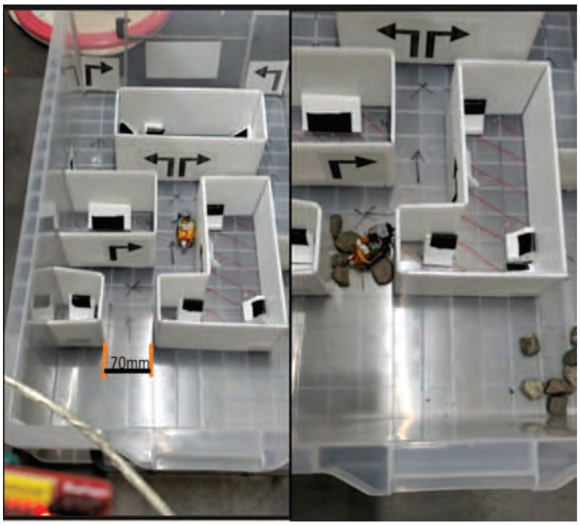

Fig. 8. (Left) CameraRoach travelling in a maze-like environment. (Right) CameraRoach moving over pebbles (size shown).

in some cases the cockroach's body tilts but in its natural environment like on the ground with mud/sand the cockroach was able to move well as its legs were able to get a better grip due to the texture of mud/sand.

Several authors used different stimulation parameters that is more suitable to their set up of the cyborg insect backpack. Based on the insect they used, based on the different type of stimulation (for example some used cockroaches stimulating their neurons, some used beetles, and some used moths and simulated their flight muscles), the stimulating signal frequency and duty cycle changed. **Table 2** shows stimulation profiles of different cyborg insects. Our camera roach insect uses a 20 ms pulse, however depending on the response of the insect, the pulse width is initially calibrated ranging from 1 ms to 20 ms because of the surgical variance in the depth at which the electrode is inserted into the antenna and the electrode-antenna tissue bonding.

We tested CameraRoach by stimulating it to guide through a maze (**Fig. 8**, left). However, we found that the cockroach does not obey the stimulation signals always but there is some amount of autonomy to its gait; it tends to follow walls autonomously, so to guide it in a lane one needs to just give the forward stimulus to the cerci. We also found that if we give the stimulation pulses too long, the cockroach seems to be able to ignore them. So, is better to stimulate it irregularly with the joystick. Some level of difficulty was encountered at the intersections to make it turn sometime the cockroach would turn more than the required amount and would oscillate. We expect this effect to become less and less as the operator gets familiar with the controls. We successfully tested that CameraRoach can navigate based only on the onboard camera feedback. The only environment features added were arrows posted in the maze. Looking at the arrows, wall openings, and edges of the maze walls, we were able to make the CameraRoach turn appropriately, as shown in **Figs. 8–12**. We did surgery on about 40 cockroaches. The surgery success rate is only 33%. One in only 3 cockroaches responds to all stimulus, meaning the stimulus works in activating the neuron in both the left and right antennae and cerci at the back in about 33% of the cockroaches. Earlier we found that due to fungus built up in the box in the cockroach due to lack of enough aeration the fungus would kill the cockroach, so later we observed this and provided more ventilation to the storage container (terrarium) of the cockroach. We also provided timely water and food to the cockroach. All this increased the survival rate and now they survive up to 2.5–3 months from the date of surgery.

3.2. Comparison with Beetle-Cam (Advantages and Disadvantages)

A comparison of the hardware features of the Beetle-Cam and our CameraRoach is shown in **Table 3**. CameraRoach is more suitable for search and rescue because it can be navigated remotely, and it provides the live camera feedback of its surrounding. Through WiFi, we were able to connect with CameraRoach throughout our university campus. As we use a WiFi SOC, CameraRoach has a higher bandwidth (compared to Beetle-Cam) and can transmit live a high-resolution image and video up to 1080 p at a frame rate of 25.6 fps.

With Bluetooth Beetle-Cam paper mentions a higher distance of transmission with a battery usage time between 68 to 260 min which is 2 to 8 times higher than using our WiFi boards. Also their Bluetooth system is very lightweight. Energy efficient and battery usage time are the limitations in our WiFi daughter boards when compared to Bluetooth technology. The video feed lasts to a maximum distance of 30 m, whereas the WiFi neural stimulus packet still can be sent at a higher distance of 40 m or more. The WiFi neural stimulation packet is smaller compared to video frames at 640×480 or 320×240 and they can be sent at longer distances.

Machine vision techniques are used to analyze the motion of the cyborg cockroach through the maze. We used computer vision algorithms like RGB color filter, blob tracking and bounding box to track the position of the cockroach in the maze and plot its trail through the maze. It was observed that our stimulation and control technique are very sound to make the cyborg cockroach turn in place and negotiate 90° turns. The bounding box tracking is not exactly accurate due to occlusion but gives us a decent estimate of the cockroach's approximate path in the maze as the pixel tracking error is within the width of the insect. This was plotted against ground truth in **Fig. 13**. The ground truth was taken from manually marking the cockroach position in the video frames.

We did WiFi range tests with a single router and also tested our system with an established WiFi network in the university campus and found that the cockroach can work in a large geographical area with WiFi network established. This is important because when it comes to urban search and rescue it would be possible to quickly

Table 2. Stimulation parameters of various cyborg insect works.

No.	Cyborg insect stimulation specifications			
	Author	***Insect platform***	***Waveform parameters***	***Attributes***
1	Whitemire et al. (2013)	Gromphadorhina portentosa	Pulse	PWM
2	Whitmire et al. (2014)	Gromphadorhina portentosa	30 ms pulse	50% duty cycle
3	T. Latif et al.	Gromphadorhina portentosa	30–50 ms pulse	50% duty cycle for 200–500 ms
4	H. Sato et al. (2008)	Cotinis texana beetle	Pulse train	2 Hz, 10 Hz, and 100 Hz
5	H. Sato et al. (2009)	Mecynorhina beetle	100 Hz pulse train	20% duty cycle
6	Faulkner	Cockroach	55 Hz pulse	50% duty cycle
7	Dirafzoon et al.	Periplaneta americana	Pulse train	
8	Bozkurt et al.	Manduca sexta moth	5 V pulse	Biphasic
9	Sriranjan et al.	Gromphadorhina portentosa	3.3 V pulse	20 ms PWM signal

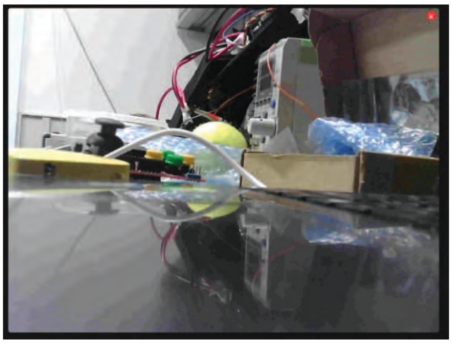

Fig. 9. A still from the CameraRoach's cam at 1600×1200 resolution.

Fig. 10. View from camera onboard the cyborg insect.

Fig. 11. Cockroach motion turning going straight and then turning right.

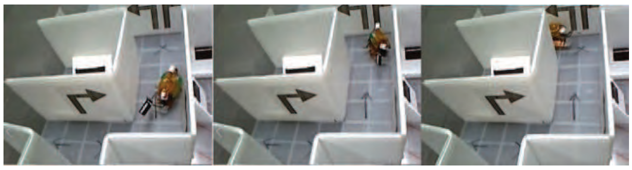

Fig. 12. Cockroach motion turning going straight and then turning left.

Table 3. A comparison of CameraRoach and Beetle-Cam.

No.	CameraRoach and Beetle-Cam comparison		
	Feature	***Camera-Roach***	***Beetle-Cam***
1	Resolution	2048×1536	160×120
2	Color mode	RGB	B/W
3	Face tracking	Yes	No
4	White balance	Yes	No
5	Gain setting	Yes	Yes
6	Frame rate	1–25 fps	1–6 fps
7	Wireless technology	WiFi	Bluetooth
8	Data rate	20 mbps	2 mbps
9	Microcontroller/Processor	ESP32	NRF 528232
10	Battery duration	35 min	60–260 min

setup a temporary WiFi network with multiple routers and antenna to use this WiFi cyborg insect as envisioned in the simulation of Bozkurt et al. [14]. We found that as the distance from the cyborg insect backpack increased, the frame rate and the resolution fell. So, for example at a distance of 25 m, we would get still image at 640×480 resolution but we would get 3 fps at 320×240. We tabulated our results in **Table 4**. We also added a pivot turn feature, where we press the button of a joystick and with the smallest possible stimulation step the cockroach will turn either left or right.

Figure 14 shows the decreasing resolution as mentioned in **Table 4** during WiFi range tests. We used the Smart Mini portable router from GL-INET operating at 5 V and max. 1 A that is USB powered. Using this WiFi technology, it would be possible to search through crevices and narrow passages in the debris in a search and rescue scenario. WiFi brings high frame rate, and it can result in decreasing the navigation time. If the frame rate is low and a resolution is low, then the insect will have to move slowly, and this will increase the time of navigation. For example, if the frame rate is half or one fourth then what could it takes. Right now, we have about 3500 frames for half the maze navigation but if it was 300 then there will be frame lag and turn by turn navigation would not be possible or it would be so slow that it would be practically not easy to do navigation with the insect. Higher frame rate and energy consumption are useful when fitting through pipes and crevices. At range of

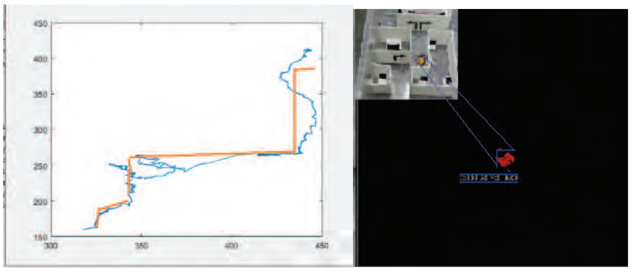

Fig. 13. (Left) Path of the cockroach as tracked by camera, blue path is tracked with pixel error and orange path is ground truth. *X*-*Y* axes are the camera axes in pixels. (Right) Cockroach tracked after applying filters.

Table 4. CameraRoach distance vs. frame rate WiFi tests.

No.	CameraRoach WiFi Range test of camera			
	Distance	*Stimulation signal*	*Resolution*	*Frame rate (FPS)*
1	10 m	ON	640×480	6.1
2	15 m	ON	320×240	6.1
3	20 m	ON	320×240	6.1
4	25 m	ON	640×480	Still image
5	30 m	ON	160×120	3
6	35 m	ON	160×120	1
7	40 m	ON	160×120	0.3

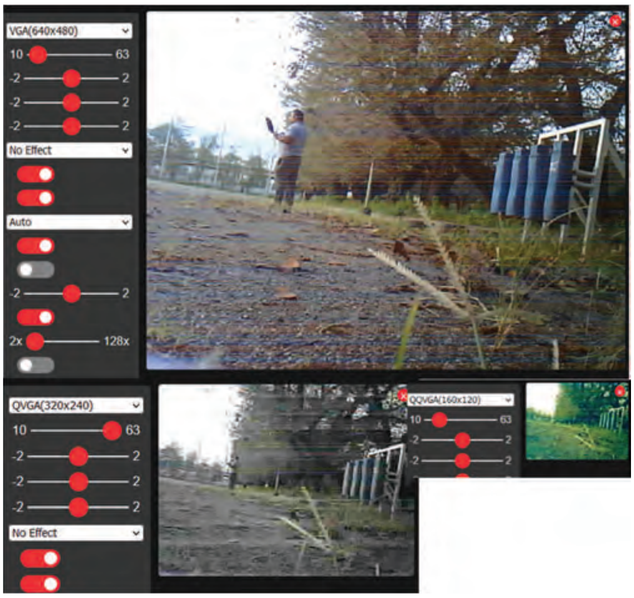

Fig. 14. Pictures captures at decreasing resolution starting from 640×480 then 320×240 and last 160×120 at increasing distance from 10 m, 20 m, 40 m during WiFi range test with the router.

40 m there is no possibility of first person view with navigation control as live video fails, we can only grab still images at 40 m but when it comes to closer distances like 30 m slow navigation first person view control is possible and this is better at further low distances like 15 m or 20 m as first person view navigation has been tested to work. We also implemented pivot turn feature where a small stimulation signal of 1 ms makes the cockroach turn slightly by 10° towards the left or right whereas the Beetle-Cam uses a miniature actuator arm for pivoting the camera. This would be useful to pan the camera when performing the operation of search.

4. Conclusions and Future Research

We designed and implemented a backpack containing a WiFi equipped miniature camera and neuro-stimulation hardware that can be mounted on a cockroach. The backpack was mounted on a Madagascar hissing cockroach and we demonstrated that the cockroach can be navigated via remote-control through a maze and can send live video feedback of its surroundings. In the future, we plan to add autonomous capabilities like self-navigation via SLAM. We are also experimenting with mounting a thermal camera on CameraRoach to help in search-and-rescue missions. Some future idea is to use GPS with camera and dual camera system with thermal camera [15]. In our current implementation, one limitation is the battery life. To overcome this, one approach is to create a self-powered cyborg cockroach by feeding the cockroach a particular sugar compound named trehalose, which makes an autonomously powered battery [17, 18]. However, this requires making a large incision in the cockroach body to fit the enzymatic tube and battery's cathode and anode, which is a disadvantage. We plan to improve the battery life by reducing the transmit gain and by using the NDB diamond battery [e, f]. NDB battery is a miniature diamond-based battery where a radioactive carbon-14 and resultant of the reaction are the flow of electrons which generates current and voltage difference. These batteries can run for a period of several years as already proved to work in this article. The NDB battery is compact, lightweight, and has a long run time, and thus is very much suited for cyborg insect application.

Acknowledgements

This research was partially supported by a grant from the Doctoral Program for World-leading Innovative & Smart Education of Tokyo University of Agriculture and Technology (TUAT) granted by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

References:

[1] V. Iyer et al., "Wireless steerable vision for live insects and insect scale robots," Science Robotics, Vol.5, Issue 44, eabb0839, doi:10.1126/scirobotics.abb0839, 2020.

[2] E. Whitmire et al., "Acoustic Sensors for Biobotic Search and Rescue," SENSORS (2014 IEEE), pp. 2195-2198, doi: 10.1109/ICSENS.2014.6985475, 2014.

[3] R. D. Arnold et al., "Search and rescue with autonomous flying robots through behavior-based cooperative intelligence," J. of Int. Humanitarian Action, Vol.3, 18, doi: 10.1186/s41018-018-0045-4, 2018.

[4] H. Sato et al., "Cyborg beetle insect flight control through implantable, tetherless microsystem," Proc. of the 2008 IEEE 21st Int. Conf. on Micro Electro Mechanical Systems, pp. 164-167, doi:10.1109/MEMSYS.2008.4443618, 2008.

[5] T. Latif and A. Bozkurt, "Line Following Terrestrial In-

sect Biobots," Proc. of the Int. Conf. of the IEEE Engineering in Medicine and Biology Society, pp. 972-975, doi: 10.1109/EMBC.2012.6346095, 2012.

[6] C. F. Herreid II and C. R. Fourtner (Eds.), "Locomotion and Energetics in Arthropods," Springer Science & Business Media, doi: 10.1007/978-1-4684-4064-5, 1981.

[7] A. Dirafzoon et al., "Biobotic motion and behavior analysis in response to directional neurostimulation," Proc. of the IEEE Int. Conf. on Acoustics, Speech and Signal Processing (ICASSP), pp. 2457-2461, doi: 10.1109/ICASSP.2017.7952598, 2017.

[8] E. Whitmire, "Kinect-based system for automated control of terrestrial insect biobots," Proc. of the 35th Annual Int. Conf. of the IEEE EMBS, pp. 1470-1473, 2013.

[9] J. Cole et al., "A study on motion mode identification for cyborg roaches," Proc. of the 2017 IEEE Int. Conf. on Acoustics, Speech and Signal Processing (ICASSP), pp. 2652-2656, doi: 10.1109/ICASSP.2017.7952637, 2017.

[10] T. Latif et al., "Towards Fenceless Boundaries for Solar Powered Insect Biobots," Proc. of the 36th Annual Int. Conf. of the IEEE Engineering in Medicine and Biology Society, pp. 1670-1673, doi: 10.1109/EMBC.2014.6943927, 2014.

[11] A. Dirafzoon, "Cyborg-Insect Networks for Mapping of Unknown Environments," Proc. of the ACM/IEEE Int. Conf. on Cyber-Physical Systems (ICCPS), pp. 216-216, doi: 10.1109/ICCPS.2014.6843729, 2014.

[12] E. Faulkner and A. Dutta, "Microcircuit Design for Real-Time Data Acquisition and Neuromuscular Control of Insect Motion," Proc. of the 2018 Conf. on Cognitive Computational Neuroscience, PS-1A.43, doi:10.32470/CCN.2018.1207-0, 2018.

[13] A. Dirafzoon, A. Bozkurt, and E. Lobaton, "A framework for mapping with biobotic insect networks: From local to global maps," RAS J., Vol.88, pp. 79-96, 2016.

[14] A. Bozkurt, E. Lobaton, and M. Sichitiu, "A Biobotic Distributed Sensor Network for Under-Rubble Search and Rescue," Computer, Vol.49, Issue 5, pp. 38-46, doi: 10.1109/MC.2016.136, 2016.

[15] P. T. Tran-Ngoc et al., "Insect-Computer Hybrid System for Autonomous Search and Rescue Mission," arXiv, doi: arXiv-2105.10869, 2021.

[16] A. Bozkurt et al., "Mems based bioelctronic neuromuscular interfaces for insect cyborg flight control," Proc. of the 2008 IEEE 21st Int. Conf. on Micro Electro Mechanical Systems, pp. 160-163, doi: 10.1109/MEMSYS.2008.4443617, 2008.

[17] J. Schwefel, "Wireless Communication by an Autonomous Self-Powered Cyborg Insect," J. of The Electrochemical Society, Vol.161, No.13, pp. H3113-H3116, 2014.

[18] K. Shoji et al., "Bio-fuel cell backpacked insect and its application to wireless sensing," Biosensors and Bioelectronics, Vol.78, pp. 390-395, doi: 10.1016/j.bios.2015.11.077, 2016.

Supporting Online Materials:

[a] H. Pozniak, "Finders, keepers: search and rescue robots evolve." https://eandt.theiet.org/content/articles/2020/01/finders-keepers-search-and-rescue-robots-evolve/
[Accessed April 3, 2021]

[b] Backyard Brains, "RoboRoach Experiment #1 – Neural Interface Surgery," 2021. https://backyardbrains.com/experiments/files/RoboRoachExperiment-NeuralInterfaceSurgery.pdf [Accessed August 20, 2019]

[c] S. Rasakatla et al., "CameraRoach: cyborg cockroach," Demo video 1. https://www.youtube.com/watch?v=rtruDesWV_M [Accessed October 16, 2020]

[d] S. Rasakatla et al., "Cyborg Insect: CameraRoach," Demo video 2. https://www.youtube.com/watch?v=_YYbo-BfdmQ [Accessed April 27, 2021]

[e] University of Bristol, Cabot Institute for the environment. https://www.bristol.ac.uk/cabot/what-we-do/diamond-batteries/ [Accessed October 16, 2020]

[f] NDB diamond battery. https://ndb.technology/ [Accessed October 16, 2020]

Name:
Sriranjan Rasakatla

Affiliation:
Ph.D. Student, Mizuuchi Lab, Tokyo University of Agriculture and Technology

Address:
2-24-16 Nakacho, Koganei, Tokyo 184-0012, Japan

Brief Biographical History:

2006-2009 Bachelors in Engineering, Osmania University
2009-2013 Masters by Research, Robotics and Human Computer Interfaces, International Institute of Information Technology, Hyderabad (IIIT-H)
2013-2016 Senior Robotics Engineer, UURMI Systems, Hyderabad India (Currently Mathworks Hyderabad)
2016-2019 Senior Research and Development Consultant, Impressive Applications, London Ltd.
2020- Research Assistant, Sony AI

Main Works:

- S. Rasakatla and K. M. Krishna, "WAY-GO torch: An intelligent flash light," Proc. Int. Conf. on Robotics and Biomimectics (ROBIO 2013), Shenzhen China, pp. 1765-1771, 2013.
- "Design, construction and a compliant gait of "ModPod": A modular hexpod robot," Proc. Int. Conf. on Robotics and Biomimectics (ROBIO 2010), Tianjin China, pp. 1341-1345, 2010.
- S. Rasakatla and K. M. Krishna, "Snake P3: A semi-autonomous Snake robot," Proc. Int. Conf. on Robotics and Biomimectics (ROBIO 2010), Tianjin China, 2010.
- S. Rasakatla and K. M. Krishna, "RAMA-1 highly dexterous 48DOF robotic hand using magnetic spherical joints," Proc. Int. Conf. on Robotics and Biomimectics (ROBIO 2013), Shenzhen, China, pp. 816-823, 2013.
- S. Rasakatla, I. Mizuuchi, and B. Indurkhya, "An EMG leg for biker amputees with gear control," Proc. Int. Conf. on Biomedical Robots and Biomimectics, 2020.
- S. Rasakatla, T. Suzuki, W. Tenma, I. Mizuuchi, and B. Indurkhya, "CameraRoach: Various Electronic Backs Packs for Search and Rescue," ROBIO, 2021.
- S. Rasakatla, A. Ueno, A. Galiza, T. Ario, I. Mizuuchi, and B. Indurkhya, "An anthropomorphic surgical simulator arm based on series elastic actuators with haptic feedback," Proc. Int. Conf. on Robotics and Biomimectics (ROBIO 2021), 2021.

Name:
Wataru Tenma

Affiliation:
Department of Applied Biological Science, Tokyo University of Agriculture and Technology

Address:
2-24-16 Nakacho, Koganei, Tokyo 184-0012, Japan

Brief Biographical History:
2018- Undergraduate Student, Tokyo University of Agriculture and Technology

Main Works:
• "UV tolerance in the two-spotted spider mite, Tetranychus urticae," J. of Insect Physiology, Vol.55, pp. 649-654, 2009.

Name:
Takeshi Suzuki

Affiliation:
Associate Professor, Graduate School of Bio-Applications and Systems Engineering, Tokyo University of Agriculture and Technology

Address:
2-24-16 Nakacho, Koganei, Tokyo 184-0012, Japan

Brief Biographical History:
2008- JSPS Research Fellow, Kobe University
2010- JSPS Research Fellow, Chiba University
2013- Part-Time Researcher, Ibaraki University
2014- JSPS Postdoctoral Fellow for Research Abroad, The University of Western Ontario
2015- Associate Professor, Tokyo University of Agriculture and Technology

Main Works:
• "RNAi-based reverse genetics in the chelicerate model Tetranychus urticae: A comparative analysis of five methods for gene silencing," PLoS ONE, Vol.12, e0180654, 2017.
• "Photo-orientation regulates seasonal habitat selection in the two-spotted spider mite Tetranychus urticae," J. of Experimental Biology, Vol.216, pp. 977-983, 2013.
• "UV tolerance in the two-spotted spider mite, Tetranychus urticae," J. of Insect Physiology, Vol.55, pp. 649-654, July 2009.

Membership in Academic Societies:
• The Acarological Society of Japan
• The Japanese Society of Applied Entomology and Zoology (JSAEZ)
• Pesticide Science Society of Japan (PSSJ)

Name:
Bipin Indurkhya

Affiliation:
Professor of Cognitive Science, Jagiellonian University

Address:
24 Gołębia, Kraków 31-007, Poland

Brief Biographical History:
1981 Received Master's degree in Electronics Engineering from Philips International Institute of Technological Studies
1985 Received Ph.D. in Computer Science from University of Massachusetts Amherst

Main Works:
• B. Indurkhya, "Metaphor and Cognition: An Interactionist Approach," Springer Science & Business Media, 1992.
• M. D. Gineste, B. Indurkhya, and V. Scart, "Emergence of features in metaphor comprehension," Metaphor and Symbol, Vol.15, No.3, pp. 117-135, 2000.

Name:
Ikuo Mizuuchi

Affiliation:
Professor, Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology

Address:
2-24-16 Nakacho, Koganei, Tokyo 184-0012, Japan

Brief Biographical History:
2002 Received Ph.D. (Engineering) from The University of Tokyo
2002-2006 Project Assistant Professor, Graduate School of Information Science and Technology, The University of Tokyo
2006-2009 Lecturer, Department of Mechano-Informatics, The University of Tokyo
2009-2020 Associate Professor, Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology
2020- Professor, Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology

Main Works:
• Musculoskeletal robots, robot dynamics
• Home robots, kitchen robots, agricultural robots
• Human-robot interaction

Membership in Academic Societies:
• The Institute of Electrical and Electronics Engineers (IEEE)
• The Japan Society of Mechanical Engineers (JSME)
• The Robotics Society of Japan (RSJ)