A SOLUTION PATH FOR SEARCH AND RESCUE AND REHABILITATION THROUGH ROBOTICS

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1. INTRODUCTION

The solution chain for search and rescue and rehabilitation:

Imagine if there is a natural calamity like an earthquake or a tsunami and there is need for search and rescue with people stuck under the debris. We need a solution for this problem to save the lives of people. What I purpose is that we can use cyborg insects and snake robots to search for the people stuck under the debris, we can improve the process of search so that rescue help will come even faster and if the time for search can be reduced then more lives will be saved. After pulling out the survivors form the debris, we can employ doctors who are experienced in robotic surgery for preoperative training and operative procedures using robots to treat the wounded people. Then we can use robotic surgical arms and simulators to train the doctors in robotic surgery to treat the survivors. After the surgery if any survivor has lost a limb, then we can use prosthetic arms and legs to restore some part of the lost functionality of their limbs. This end-to-end chain as a solution to the problem of search and rescue and rehabilitation is my doctoral thesis. I now explain the solution to individual problems here.

Search and rescue robots need multiple terrain or all terrain mobility. This has been observed in insects like cockroaches so well. They effortlessly move over uneven terrain for their size, go over sand, gravel, rocks, grass and plants. They can fit through small holes, tight spaces and crevices. Some researchers have developed all terrain mobility robots like this robot with tracked flipper mechanism [1][2] but they are too large to fit into tight spaces or holes or look under debris. Wheeled robots without a suspension mechanism like a rocker bogie or spring mounted wheels immediately loose ability when the surface is not flat.

So for an Urban SAR (search and rescue) where people are stuck under the debris we need robots which can fit in narrow space and move. Here is another example of a wheeled robot with an attached driller and a gripper for search and rescue which still lacks the ability to do all terrain locomotion. Classically Shigeo Hirose has built several novel structures or slender snake robots and CMU Bio robotics group has also worked on making snake robots fit through tight spaces, so it makes sense from their existing efforts that we can also work on tight space fitting robots for search and rescue. Snake robots can fit through holes and crevices of one size but even smaller spaces can be accessed by cyborg insects.

IOT devices[3] have been used in the process of search and rescue but they do not show any system implementation or a practical usage scenario on what kind of robot to use it. Use of a network of cyborg insects in theory was proposed by a group of cyborg cockroach researchers called the biobotic node[34] but it was only shown in simulation with wheeled robots in a poster [cite reference].Multi-robot platforms[4] for search and rescue system with a drone and a mini wheeled robot with suspension with reverse signal strength based location system but still not suitable for search and rescue as there is no search function with a camera or camera based navigation with the ability to do all terrain locomotion.

Taking this idea one step one way[5] was to introduce sonar based mapping and localization on a mobile robot with a UAV but this also does not fit for tight space search and rescue usage or search function. So we devised a cockroach robot with a camera that can be neurally controlled to a guided exploration and search. And we also took the audio route because on cockroaches it does not work in rubble but before fitting through the final element of the rubber if we can scout on top of the rubble with a snake robot to search for survivor help cries and then use a cockroach robot to do further guided exploration, I think we can improve the over all process of search and rescue.

In the future we can individually use a wheeled robot with a UAV scout I the air to take the snake robot and cockroach robot to the site of disaster using transport by road and when there is a need of all terrain locomotion we can then deploy these robots appropriately on the all terrain rubble site. We deal with some important cases involved in the rescue situation of all terrain urban SAR scenario. The whole grail of search and rescue is a big problem but we worked on use cases showing one solution path. Search and Rescue with mobile robots has been long researched for example in paper[6] in 1997 ICAR where they use a team of mobile robots, where they describe an algorithm for team work tasks for search and reaching the target object of interest and manipulating it.

Many preliminary designs involved a tank threaded mobile robot[7] which uses multiple cameras to detect people which is better for all terrain locomotion but not small enough to fit through tight spaces. Lope robot[8] highlights the importance of the fact that urban environments which have building and step like structures etc is difficult to be locomoted by wheeled or tracked mechanisms. So they developed the novel Loper robot with tri-lobe wheel mechanism to overcome steps and rock like features but still this robot does not have the manoeuvrability of a snake robot and cannot fit in tight spaces like a cyborg insect or a snake robot can.

So that is the preliminary reason as to why we chose the snake robot and cyborg insect for our search and rescue use cases and research study. Another preliminary wheeled robot design[9] for search and rescue has been proposed. There have been multiple attempts by many researchers world wide to design search and rescue robots but they are too bulky or lack the mechanism to be used in debris as pointed out in paper [8]. An improved version[10] of a tanked threaded robot which has a partially reconfiguring freedom to overcome slopes. This is an interesting design but if it can be made miniature there it will prove more useful to urban SAR scenarios.

One work[11] shows a tracked robot as a search and rescue robot with a stereo camera setup. The stereo camera feed can be viewed by using a head mounted display which gives more situational awareness and depth perception of the environment being searched. To identify the objects of search of interest they stress the need of improving situational awareness through a camera feed and it is also remotely controlled which is need for exploration and navigation purposes in a SAR (search and rescue) situation. Using robots for search and rescue in dangerous environments that are harmful for human beings is promising area of research and application. Another work[12] shows a hybrid telematic system that uses 2 robots.

One is an autonomous mobile mapping robot and the other is a human following robot[16]. This system was devised for semi-autonomous navigation in simulated fire scenario. Some researchers[13] [17] have discussed in simulation of using a group of similar robots as a team to do co-operative search and rescue. They say that local navigation and control which involve the elements of perception, cognition, localization and motion control are needed for a robot if it has to do search and rescue in an autonomous fashion. Cyborg insect autonomy has not been achieved yet but the closest we got in our current thesis is guided remote control exploration with navigation control.

Robots provide an opportunity to go into dangerous places usual and typical to search and rescue scenarios and that is the reason why manual, semi-autonomous and autonomous providing an interesting chance for this research. They augment the capabilities of the rescue workers who put their life at risk while working in SAR scenario. Thus if we can improve the process of search, aid the search and rescue worker and provide an improvement in this process then we can save more lives. The paper[14] provides review of robots for search, extraction, evacuation and medical field treatment. They have mentioned several mid-sized tracked mobile robots with manipulators and cameras to assist the process of search.

Some of the search robots mentioned are Soryu III, iRobot packbot, Inkutun VGTV extreme, Inkutun micro VGTV for the process of search. For the purpose of rescue they have review robots like iRobot Valkyrie, REX, BEAR, CRONA etc. Evacuation was done by robots like Lockheed, REV, Lockheed SMSS and for surgical treatment they have described robots like Da Vinci, RAVEN and Trauma Pod. Here in the conclusion they have suggested a custom solution in the form of a mobile robot that can navigate with GPS in an all terrain way using tracks and also is provided with mobile manipulator robotic arms.

Some interesting robots[15] built focus on the amazing technology developed here primarily in Japan for the purpose of search and rescue using robots. It mentions the helicopter search robot by Nakanishi of Kyoto university, jumping robot to overcome rock like obstacles by Tuskagoshi from Tokyo Institute of Technology, Soryu snake like threaded modular robot from Tokyo university of technology, Moira snake like modular robot by Osuke from Kobe university, 3D mapping from Nakanishi of Kobe university, Snake type KOHGA robot was also presented in this paper along with few mobile robots for the purpose of search and rescue navigation. They have also presented about RoboCup Rescue Japan Open 2004. Here is another preliminary robot with IP based camera which is for alive human detection with the help of a camera. Another poster paper mentions about using a distributed approach using object-oriented programming model for the purpose of search and rescue.

Cyborg insect for search and rescue: There has been a lot of research in developing cyborg insects. We want to use a cyborg insect to search for survivors in a search and rescue scenario. For this we developed an electronic backpack which uses neural stimulation to control a cockroach's motion over WiFi. The WiFi backpack is also equipped with a camera system that sends live video feedback. All the approaches explored by other researchers in the past miss one crucial sensor which is a camera. Only Beetle-cam from Vikram Iyer incorporates a camera sensor but it does not provide any exploration capabilities of the insect. 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 with onboard camera feedback that can be navigated via remote control. We chose the Madagascar hissing cockroach as the insect on which to mount the camera pack. This cockroach is small enough to fit into crevices but also can carry a printed circuit board with power, communication, and sensor components.

Sound reactive snake robot bio inspired simulation: We present a hardware and software framework in which we use the direction of the sound source to interact with the simulation of a snake robot. We present a gamification idea (like hide and seek) of how one can use the direction of the sound and develop interactive simulations in robotics and especially use the bio-inspired idea of a snake's reactive locomotion to sound. We use multiple microphones and calculate the direction of sound coming from the sound source in near real-time and make the simulation respond to it. Since a biological snake moves away from a sound source when it senses vibrations, we bio-mimic this behaviour in a simulated snake robot. This idea can be used for developing games that are reactive to multiple people interacting with a computer, based on sound direction input. This is a novel interface and first of its kind presented in this paper. This work was published in SIGGRAPH ASIA 2020. Generally, snakes feel the sensation of vibration coming from the ground and move away from the source of sound. We can bio mimic this behaviour and show that a snake robot moves away from the source of sound. Another idea is to use the anti-biomimetic idea and make the snake robot move towards the source of sound. This idea can be used to make a snake robot sense the sound of survivors in a search and rescue scenario like people who are stuck under the debris and help find them using the all-terrain locomotion capabilities of the snake robot.

The potential possibility to several search and rescue robots is to do all terrain locomotion and have senses to find out the survivors. People who developed tracked robot vehicles as discussed earlier show a potential in all terrain locomotion and to improve this possibility we have chose a micro robot in the form of a cyborg insect and macro robot in the form of snake robot. Both insects like cockroaches and biological snakes have shown a tremendous ability to do navigate and move on different types of surfaces and environment. The work of Shigeo Hirose and Howie choset prove this form of all terrain locomotion for snake robot and thus we augmented the ability of these all terrain robots with senses like visible wavelength vision, thermal vision and sound. We show in the later chapters how our work gives incremental contributions to aspects of search and rescue and rehabilitation.

Surgical simulator: The minimally invasive like Da Vinci surgical robot is extremely expensive but a successful tool. Getting access to such a niche surgical robot all the time is difficult. Giving surgical training to new surgeon trainees is important and very much needed. Also, pre-operative planning and post-operative recovery is important. Pre-operative planning is important for high success during the surgery. So, keeping these points in mind I developed a novel surgical simulator and trainer for giving dexterity training to the motion of fingers of the surgeon trainee and also provide pre-operative planning. Our surgical simulator uses a 3D physics simulator environment to simulate the robot surgical arm and the human body cadaver. The interface to this environment is through the Leap motion human computer interface device. The fine motion of the manipulation through human fingers is tracked with the Leap motion device and replicated into the virtual surgical tool tip. The motion of the arm can also be controlled in 7 degree of freedom. As a precursor to this surgical simulator, we also provided a coarser dexterity training using a Kuka like manipulator robot named the Leapulator. The Kuka like robot is supposed to train the user hand dexterity for coarse motion whereas the Lesur surgical simulator we developed gives fine finger motion dexterity training. This work was published in SIGGRAPH 2020.

Robotic leg for amputees: Here I developed a robotic leg for amputee bike riders that enables them to change gear of the bike my using EEG signal. The EEG signal is read from the unamputated part of the leg when the amputee tries to move the muscle in the unamputated part of the leg. This gives the amputee bike rider a feeling and impression that is natural as if his leg were not amputated and be able to change the gears of the bike naturally. The robotic leg is composed of a linear actuator motor, dual IMUs for reading the posture of the robot leg, a microcontroller unit and EEG signal amplifier module. The dual IMUs are used to measure the robot leg orientation and these orientation values are used to maintain the leg parallel to the bike gear pedal. The EEG signal is read when the amputee moves his leg below the knee and then this is used to trigger a click motion with the linear actuator and thus pressing the gear pedal. We have software filters running in the microcontroller to manage errors in the EEG signal. The leg also has current and voltage sensors to detect mechanical end stop of the leg and any mechanical motion interruption which prevents the danger of over actuation and hurting the unamputated portion of the leg. This work was published in BIOROB 2020.

2.CameraRoach: A WiFi- and camera-enabled cyborg cockroach for search and rescue

As the first chapter in the thesis, we introduce our effort to create a cyborg insect with the ability to controlled navigation through neural stimulation via camera feedback. This micro robot is based on a living cockroach and thus is useful in fitting through small spaces and do all terrain locomotion. 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. We also show integration with backpacks with GPS, twin thermal camera that can aid the process of search and rescue.

2.1 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 feed 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 [18] [19], 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 [18], 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 [18], 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 several such robotic systems have been designed [40] [20]. However, another approach is to use insects that can be remotely manipulated to control their movement [21] [22], and who can send back live video or audio feed of their surroundings. Insects have naturally evolved to move around in a wide variety of terrains using different modes of locomotion [23]. 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 [24]. 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 [19] 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 electro-neural stimulation (a set of five 30ms pulses given every 400ms). 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 [25] [26], 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 [27] 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 which it would stop for 0.5 to 1s and then continue its motion. These observations are incorporated in our design of *CameraRoach*. However, in their system, they use the RF signal strength [28][37] to get information about the surroundings of the cockroach, whereas we deploy a camera to get a visual image.

Faulkner and Dutta [29] present several useful observations and guidelines for controlling an insect through neuro-stimulation. They found a 1.2V 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 [28][34] 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. [31] 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.[35] also use omnidirectional and uni-directional 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 only within the line-of-sight and 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. P.Thanh Tran-Ngoc et al [36] 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 I 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 that 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.

TABLE I. VARIOUS CYBORG INSECT BACKPACKS WITH SPECIFICATIONS

No.	**Cyborg insect backpack specifications**			
	Author (year)	***Insect platform (species)***	***Payload specifications***	***Purpose***
1	Whitemire et al. (2013)	Cockroach (*Gromphadorhina portentosa*)	PIC16F687, IA4220 RF link	Kinect based tracking and control
2	Whitmire et al. (2014)	Cockroach (*Gromphadorhina portentosa*)	Unidirectional and Omni directional mics	Microphone based search and rescue
3	Latif et al. (2012)	Cockroach (*Gromphadorhina portentosa*)	Solar powered mobile RF link	Fenceless boundary system
4	Sato (2008)	Beetle (*Cotinis texana*)	TI MSP430	Insect flight control system
5	Sato et al. (2009)	Beetle (*Mecynorhina polyphemus, Mecynorhina torquata*)	CC2431 RF chip	
6	Faulkner (2018)	Cockroach	SAMB11-ZR chip	Cockroach gait control
7	Dirafzoon et al. (2017)	Cockroach (*Periplaneta americana*)	RF transceiver	mapping
8	Bozkurt et al. (2008)	Moth (*Manduca sexta*)	Atmel ATTINY13V	EMIT based moth flight control
9	Cole et al. (2017)	Cockroach (*Gromphadorhina portentosa*)	CC2530, gyro and IMU	Motion mode identification
10	Schwefel et al. (2014)	Cockroach (*Blaberus discoidalis*)	Low voltage oscillator	Implanted fuel cell
11	Iyer et al. (2020)	Beetle (*Eleodes nigrina*)	Bluetooth vision sensor	Insect scale vision

The major difference compared to paper [18] and paper [36] is that this is the first time a first-person view navigation system has been developed on a cyborg insect. In paper [19] only external navigation (not first-person view) has been implemented. Paper [18] 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 Wireless Fidelity technology onto a board that is small and light weight enough such that it could be carried by an insect. We practically achieved large field of view of about 1600x1200 pixels, colored image transmission, with a low latency control of about 90ms because we were able to send about 10 packets of navigation data or more in about 1 second. The situational awareness improves with a high-resolution image/video from the onboard 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 is necessary than when compared to Bluetooth.

Also, our idea is to develop several electronic backpacks for cyborg insects especially a cockroach that can be used for the purpose of search and rescue. The primary idea is that we can not only the make the cockroach navigate through stimulation but also get additional sensor information about surrounds like camera feed from visual wavelength camera, thermal video feed from thermal camera and also get location information using a GPS. Previously other researchers [43] [44] have used sensors like microphone to establish an audio link with survivors and locate their position through sound source localization and get video data at the scale of an insect but have not used the ability to explore with video, GPS and look for survivors with temperature sensitive cameras. Also, if such a system has to be used for search and rescue there is a need that we need to locate the survivors by getting location information from WiFi signal strength indicator or GPS. To overcome this limitation in Beetle cam we developed several electronic backpacks for the cyborg cockroach which have the ability to send visual and thermal camera frame over WiFi and some even GPS data. We selected the *Gramphadorhina Portentosa* (Madagascar hissing cockroach) because it is the biggest in the cockroach species, especially the female ones and can carry a larger payload. The cockroach can not only carry the electronics backpacks but also fit through small gaps in debris like environment thus making it ideal for a search and rescue bio bot. Our WiFi (wireless Fidelity) enabled cockroach not only provides useful sensor information over WiFi but can also be stimulated over a WiFi signal sending high resolution GPS and camera data.

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

2.2 Implementation of the CameraRoach

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

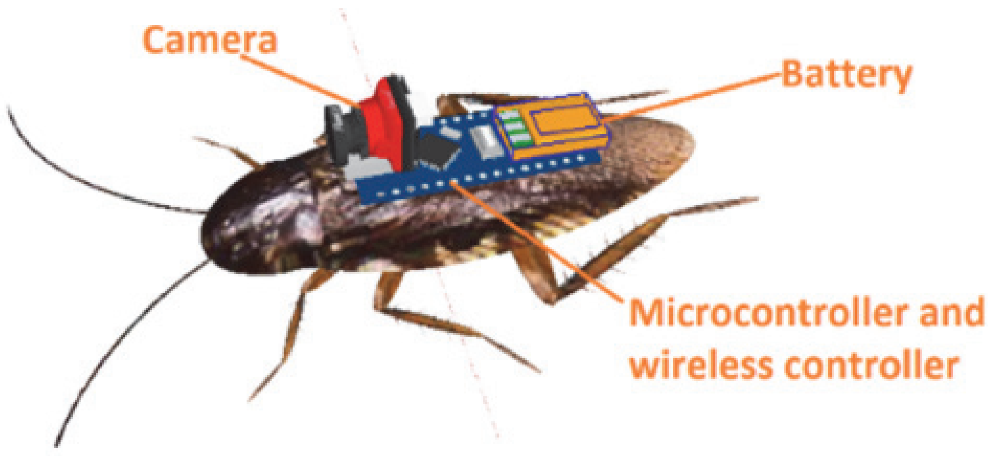


Figure 1: CAD model of the camera roach system

2.2.1 Embedded systems

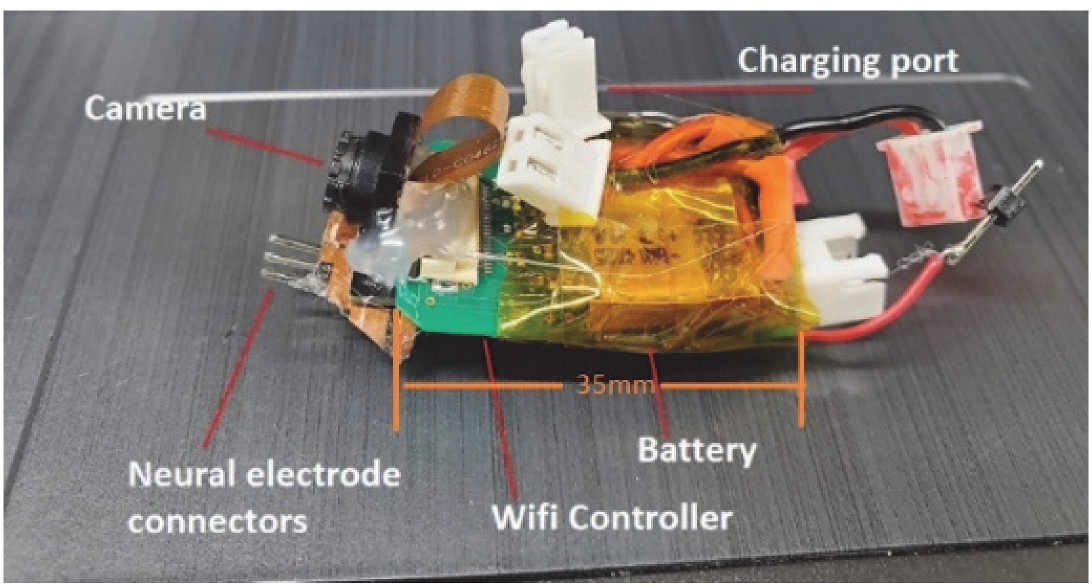


Figure 2: Wifi neural controller backpack with camera (scale bar shown)

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 prone to error. Therefore, we switched our efforts to WiFi based daughter boards (Fig 2). 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 2 and Fig. 3, left). The system is powered by an onboard 7.4V, 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.

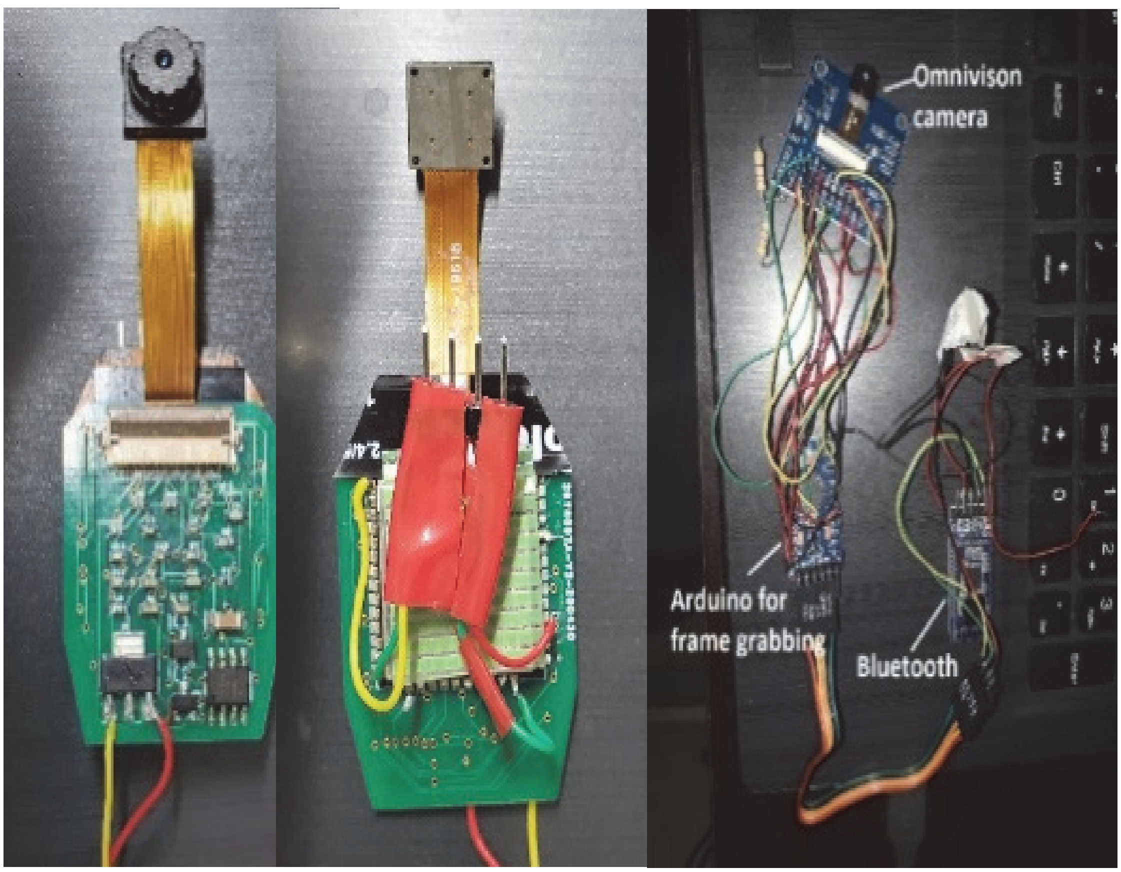


Figure 3: (Left) WiFi camera hardware; (Right) Bluetooth camera hardware

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 1ms to 20ms to see how well the cockroach would respond. In some cases, the cockroach dint respond at all indicating a failure in the surgery, some cockroaches had a good turning response for 4ms pulses, in some cases it had to increase to 10ms or 20ms 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 50-60mAh battery pack lasts only six minutes because WiFi consumes more power that 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 125mAH battery. The *CameraRoach* (Fig 4) system has a single ESP32 wrover module made by Espressif systems, manufactured in China consumes between 80mA to 260mA, running at 3.3V, OV2640 is the OmniVision camera sensor, consumes 125mW maximum power at 1.2V to 3.3V, also manufactured in China,

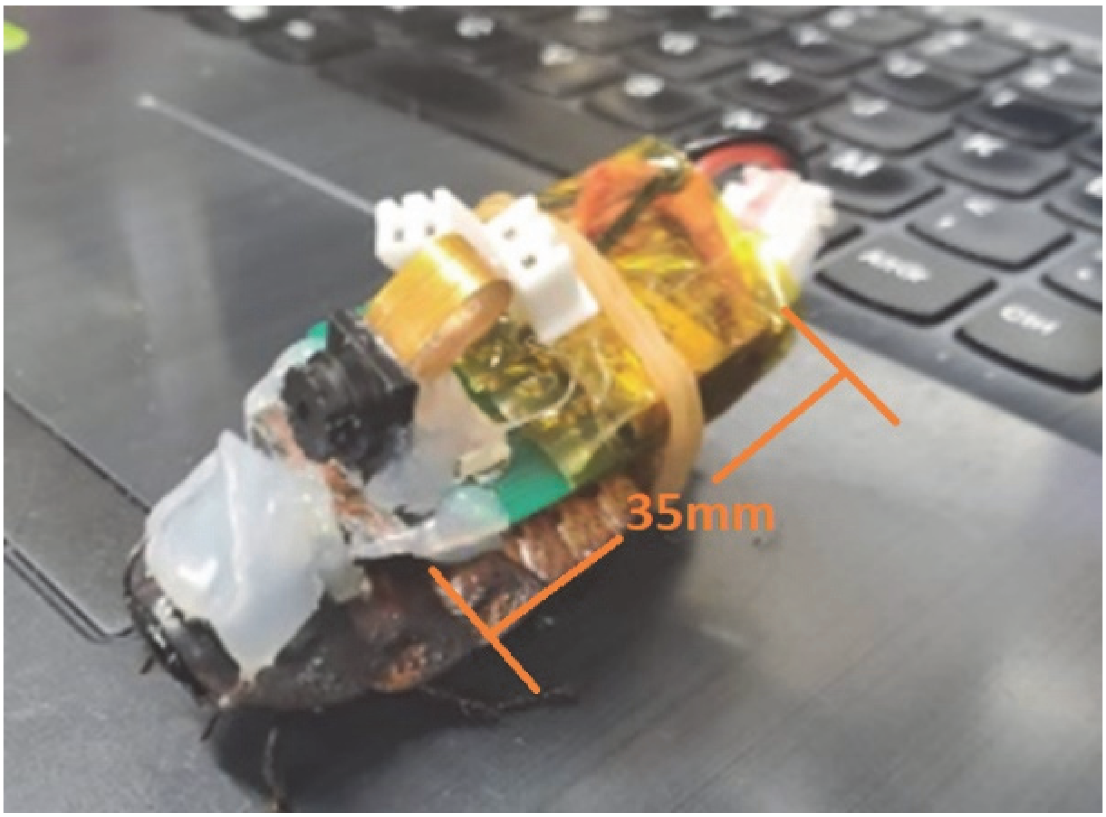


Figure 4: Cockroach with WiFi control board and camera (brown colored cockroach body beneath the green PCB, size shown)

2.2.2 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 x 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, 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 6) 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 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 ESP 32 firmware has PWM stimulation routines running which is a 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. 6 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.

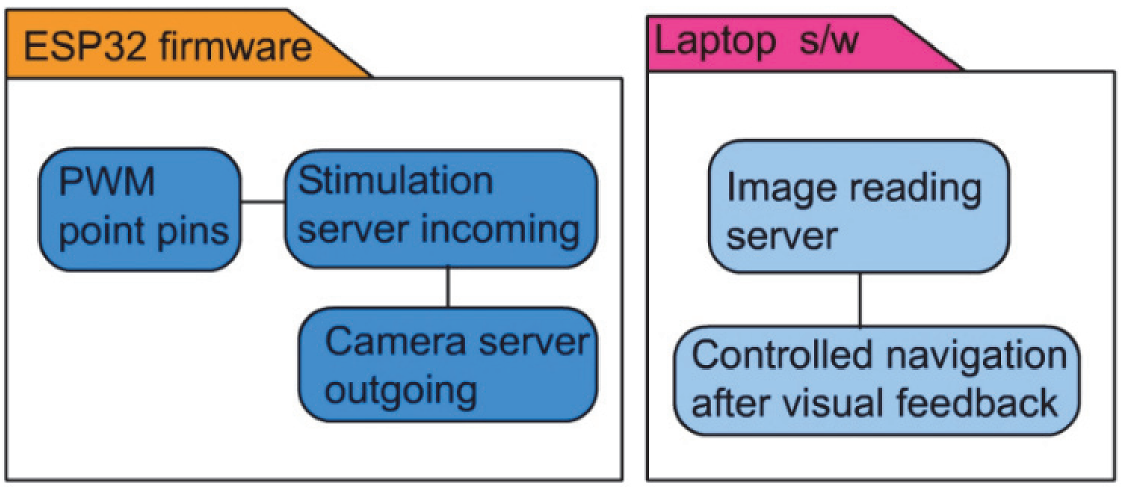


Figure 5: Software server architecture.

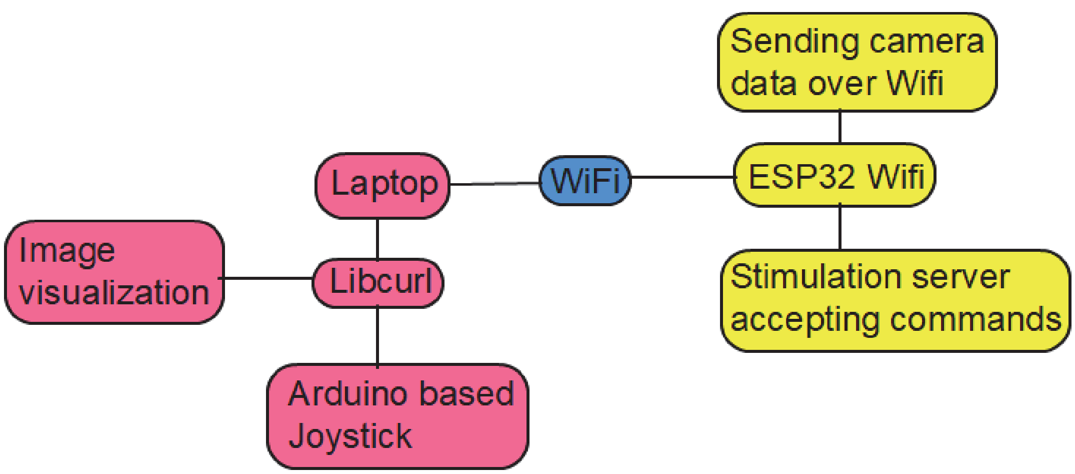


Figure 6: Hardware and software layout of CameraRoach. Yellow color indicates ESP32 side system, laptop side system is indicated in pink and the connecting WiFi bridge is indicated in blue.

Firstly, we did surgery on the Madagascar hissing cockroach [56]. We developed a twin/dual camera system with a thermal and visible wavelength camera (Fig. 7) that allows us to seal in real time the skin temperature of people possibly stuck under the debris. There was a thermal sensor solution by P.

Thanh Tran-Ngoc, et al but it does not help much in navigation as it is not pixelated feedback with a corresponding visual wavelength camera that shows a corresponding visible image. This is important because just by looking at thermal image we cannot navigate and we need a visible wavelength camera whose pixels correspond to the thermal camera image so that we can identify and collocate objects of interest, here the skin of survivors which we were able to do. Secondly, we were able to combine a WiFi GPS bridge with an established WiFi network in a geographical area like a university campus WiFi system that we can get live visible camera view with GPS location info being tracked in Google Earth. This is the first time such an integration in a system was made possible. First person view based exploration has been done for the first time in HD images, this engineering goal is important to get good information of features in the exploration space, we have also done a range vs camera resolution/frame rate testing and found our system is superior quantitatively and qualitatively compared to other insect camera systems. In Fig 6,7 we can see that there are two major software blocks running. One on the laptop end which sends motion commands received form the joystick for navigation through visual feedback and the other for accepting the images sent from onboard cyborg insect camera using Libcurl. On the insect the ESP32 microcontroller firmware has functional block to send images via the camera outgoing server and accepts motion command on one port over IP address. Also, there are blocks to generate PWM signals.

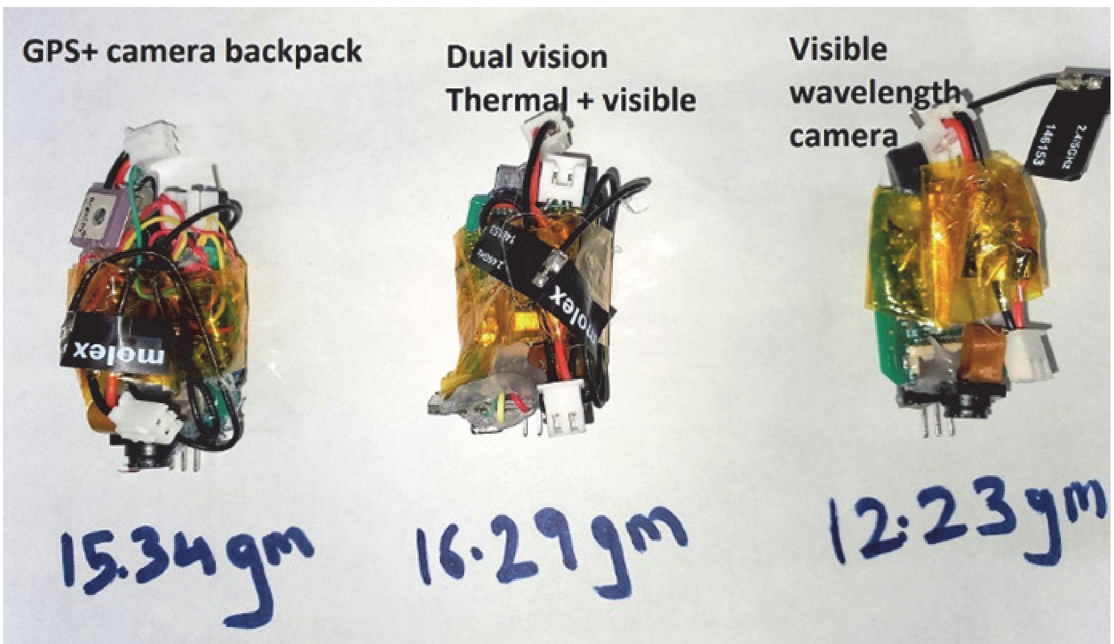


Figure 7: The 3 electronic backpacks developed for the camera roach.

2.3 Surgical Procedure

We used mature female Madagascar hissing cockroaches in this project. Each surgery was performed under a microscope (Fig. 8) by first anesthetizing the cockroach with CO2 gas. The cockroach would wake multiple times as the effect of CO2 anesthetization would wear off. CO2 anesthetization is much comfortable and faster compared other approaches like anesthetizing [30] the cockroach by keeping it in ice or in the refrigerator. As per our experience a typical session of cockroach surgery would take 40mins to 1 hour. 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 minutes whereas CO2 would put to sleep it under 1 minute. The waking up times from both CO2 and ice is almost the same which is around 10 minutes. So, CO2 helped reduced 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

Figure 8: The cockroach was put on the test table below a microscope and the electrodes were inserted through look at the microscope. Surgery done by collaborating researcher Takeshi Suzuki.

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 [13] 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. Care was taken that the bare electrodes where the insulation was stripped of and soldered to the berg strip, would not come into electrical contact 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.

2.4 Results and 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 [21] and some techniques involved early metamorphic insertion of electrodes in the pupilar stage of an insect Bozkurt et al [31]. The work of Latif et al [28] 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 did a number of experiments to evaluate the capabilities of *CameraRoach*, including its ability to be navigated through a maze and send back live camera feed. A demo video of *CameraRoach* can be seen here [41] [42]. The cockroach with the given payload of 11.2 g is able to climb over small obstacles like pebble stones (Fig. 7, 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 16gm with ease. The problem is the centre of gravity. The cockroach's body is pretty light (about 22 g), and the payload moves its centre of gravity up and 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 III 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 1ms to 20ms because of the surgical variance in the depth at which the electrode is inserted into the antenna and the electrode-antenna tissue bonding. The pulse train as observed on the oscilloscope is shown in Fig. 7.

TABLE II. STIMULATION PAREMETERS OF VARIOUS CYBORG INSECT WORKS

No.	**Cyborg insect stimulation specifications**			
	Author	***Insect platform***	***Waveform parameters***	***Attributes***
1	Whitemire 2013 et al	*Gromphadorhina portentosa*	pulse	PWM
2	Whitmire 2014 et al	*Gromphadorhina portentosa*	30 ms Pulse	50% duty cycle
3	Latif .T 2012 et al	*Gromphadorhina portentosa*	30-50 ms pulse	50% duty cycle for 200-500 ms
4	Sato. H 2008 et al	*Cotinis texana Beetle*	Pulse train	2Hz, 10 Hz and 100 Hz
5	Sato. H 2009 et al	*Mecynorhina beetle*	100 Hz pulse train	20% duty cycle
6	Faulkner 2018	Cockroach	55Hz pulse	50% duty cycle
7	Dirafzoon 2014 et al	*Periplaneta americana*	Pulse train	
8	Bozkurt 2008 et al	*Manduca sexta moth*	5V pulse	Biphasic
9	Sriranjan 2021,2022 et al	*Gromphadorhina portentosa*	3.3v pulse	20 ms PWM signal

We tested *CameraRoach* by stimulating it to guide through a maze (Fig. 7, 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. 10, 11, 15, 16, 17 and 18. 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.

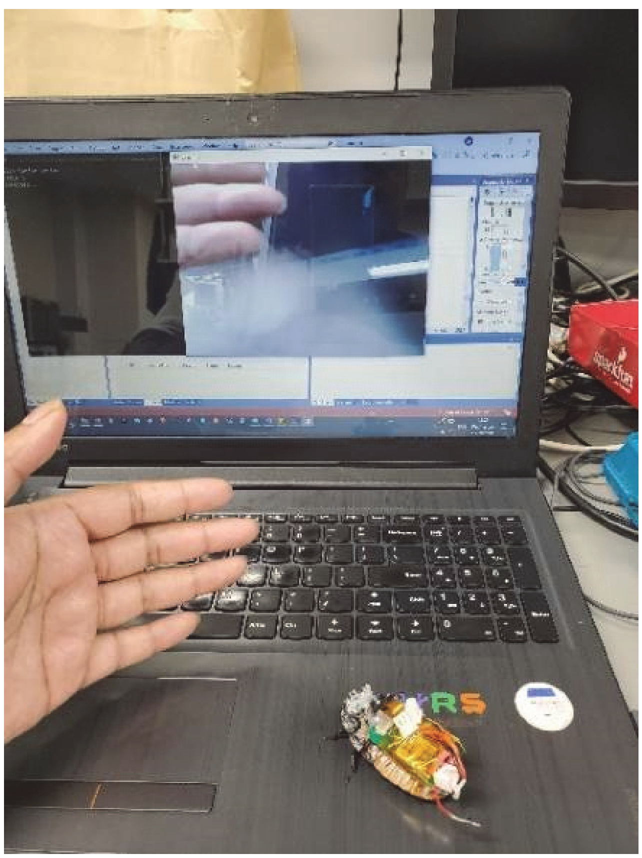


Figure 9: A still of the live video feed from CameraRoach. The camera is placed on the head of the cockroach, which is looking towards the hand of a person, and this feed is relayed over WiFi to the laptop

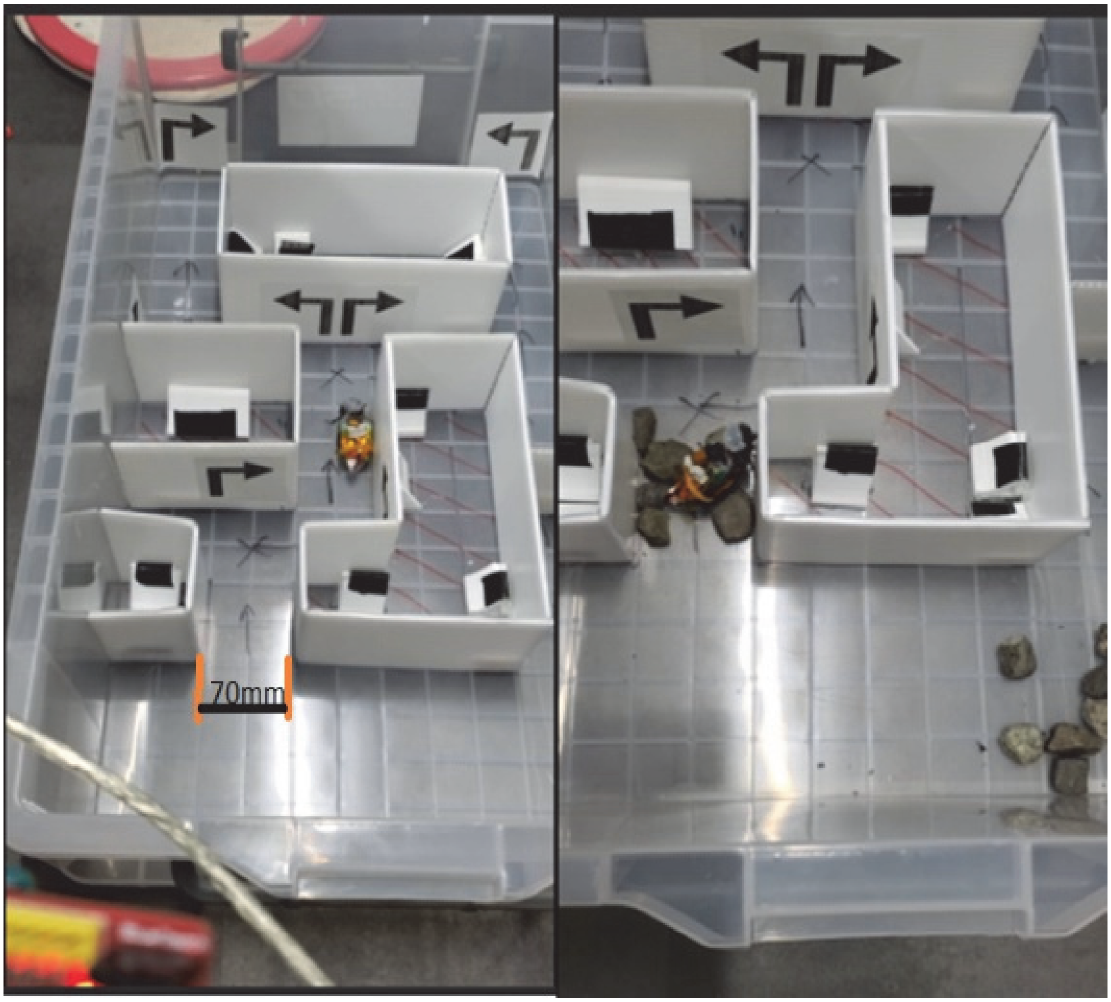


Fig 10: (Left) CameraRoach travelling in a maze-like environment; (Right) CameraRoach moving over pebbles, (size shown)

Using the CameraRoach system we can transmit a colour image upto a distance of 40m and the resolution drops with range but at a distance of 15m we can get a HD resolution image of 1600x 1200 pixels at 10-15 fps. This compares to other systems like Beetle cam is very good for first person navigation. All this was possible because of the Espressif systems WiFi SOC. We in our tests were able to connect to the WiFi camera at several locations in our WiFi enable university campus and thus it makes it ideal for Urban search and rescue compared to BeetleCam. The advantage of BeetleCam however is a long battery time because of the Bluetooth low energy radio but which comes at a cost of decreased resolution and frame rate thus bandwidth.

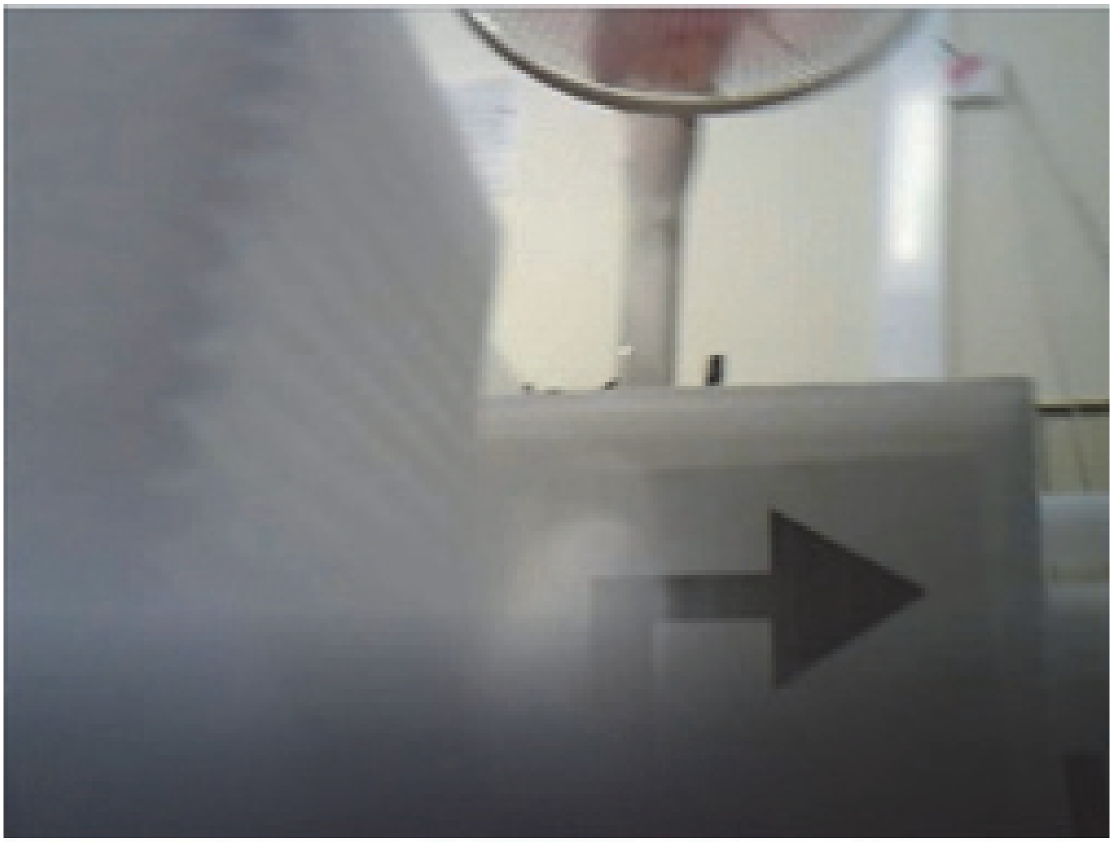


Figure 11: A still from the CameraRoach's colour video feed showing the maze navigation indicators

Extending the work further on the Cyborg insect, we developed in total 3 versions (fig 7) of the camera back pack. The 3 electronic backpacks weight between 12- 16 gms and are possible to be carried by the cockroach insect. In one board we integrated the world's smallest GPS active antenna chipset. There was a possibility to include the GPS chipset with a smaller passive antenna but passive antenna does not have a built in internal amplifier and this means that it can only work in fully open skies. Where as the active antenna GPS we used uses internal amplifier and thus it can work in partially open skies even where the sky is partially occupied by buildings and trees. We use the Origin GPS chipset

In another form of the module we combined a themal camera with a visible wavelength camera. The idea of the thermal camera was that if we have to use this CameraRoach cyborg insect in serach and rescue scenarios then we can use the thermal camera to detect for human surviors by detecting the human skin temperature. So we use the visible wavelength camera to navigate through the debris in the search and rescue scenario and then we use the thermal wavelength camera (Fig 13) to detect the human skin temperature (fig 12).

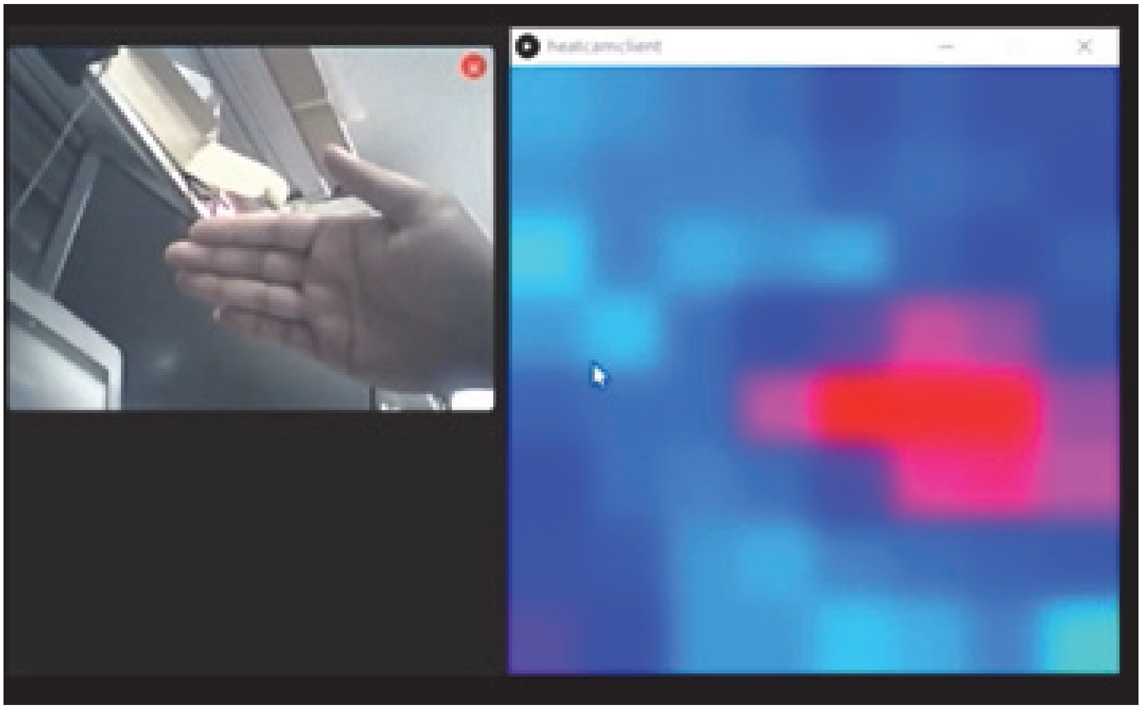


Figure 12: Dual camera backpack feed from the cyborg insect. The tracked human hand is detected in pink in the thermal image.

The thermal camera threshold can be set to human skin temperature in the software. The thermal camera we used is AMG8833 and it can detect a higher range of temperatures as well. We are using a flexible WiFi antenna in all our 3 types of eletronic backpacks to send image and sensor data over WiFi.

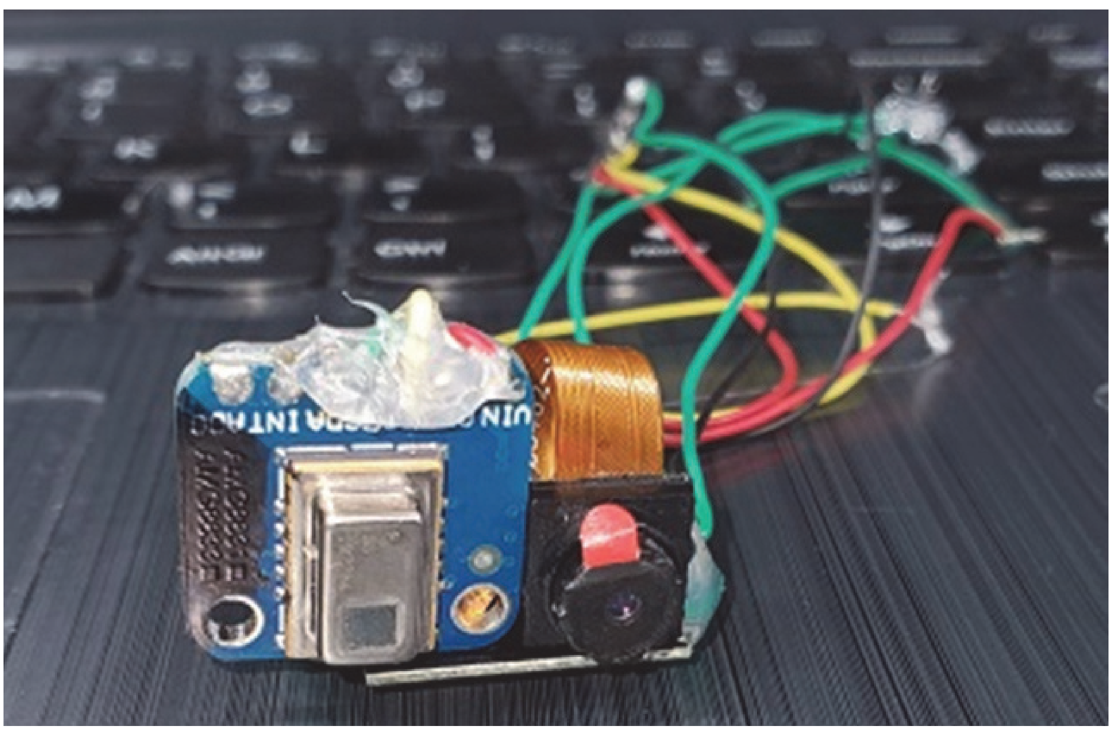


Figure 13: AMG8833 thermal I2C camera with visible wavelength camera in the insect backpack.

The picture below Fig 14 shows the GPS map of the achieved tracking. For the GPS tracking a serial over WiFi bridge hardware was constructed and software was written to echo the NMEA sentences. The resulting NMEA sentences were traked in Google Earth. Though the Origin GPS chipset we used had differential GPS with an accuracy of 2.2 meters with active antenna and more satellite visbility we were able to get sub 1 meter location fix. The GPS chipset is only 1.3 gms in weight and is of 10x 10 x 3mm in size.Demo of the thermal camera backpack and GPS is show here in reference [58][59][66].

Figure 14: Live GPS map relayed onto Google earth using the WiFi enable CameraRoach system.

2.5 Comparison with Beetle cam (advantages and disadvantages)

A comparison of the hardware features of the *Beetle-Cam* and our *CameraRoach* is shown in Table IV. *CameraRoach* is more suitable for search and rescue because it can be navigated remotely, and it provides the live camera feed 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 1080p 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 minutes which is 2 to 8 times higher than using our WiFi boards. Also their bluetooth system is very light weight. 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 meters, 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 x 480 or 320 x 240 and so they can be sent at longer distances.

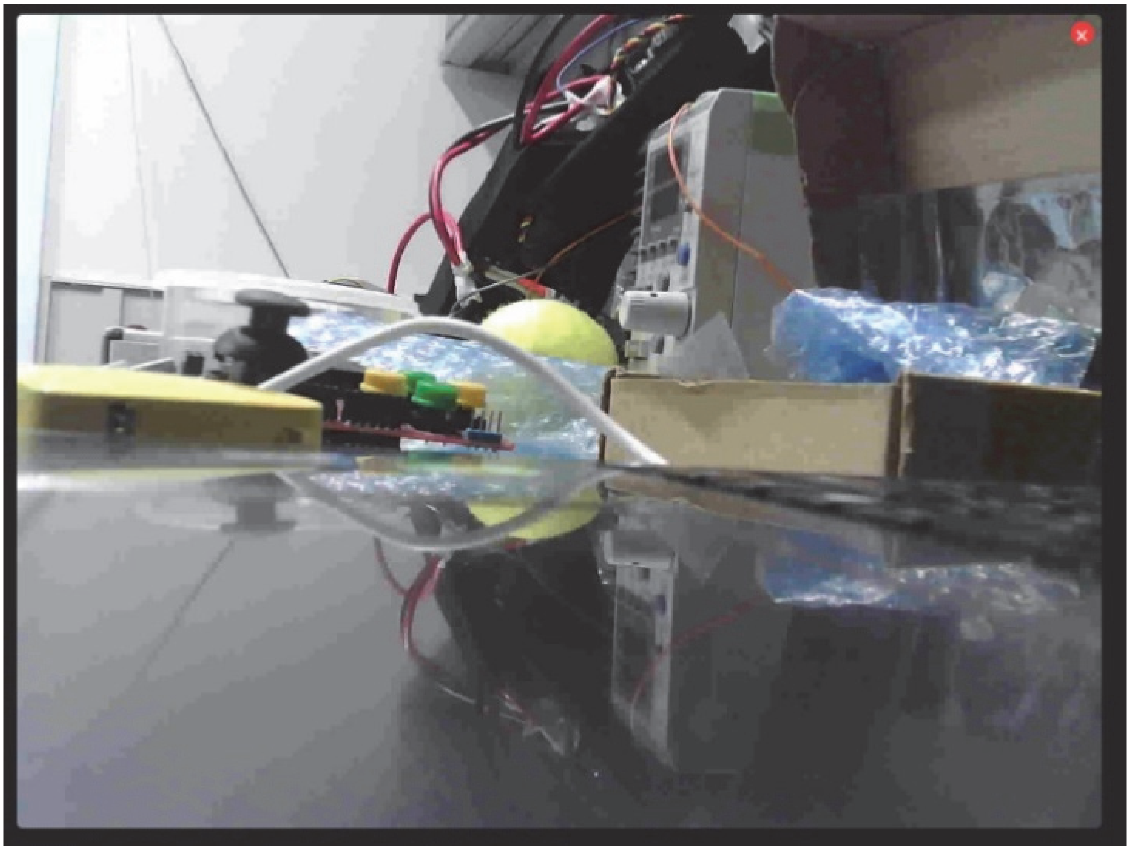


Figure 15: A still from the CameraRoach's cam at 1600 x 1200 resolution.

Figure 16. View from camera onboard the cyborg insect.

TABLE III. A COMPARISON OF CAMERAROACH AND BEETLE-CAM

No.	CameraRoach and Beetle-Cam comparison		
	Feature	***Camera -Roach***	***Beetle-Cam***
1	Resolution	2048 x 1536	160 x 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	20mbps	2mbps
9	Microcontroller / processor	ESP32	NRF 528232
10	Battery duration	35 min	60-260 min

Figure 17: Cockroach motion turning going straight and then turning right.

Figure 18: Cockroach motion turning going straight and then turning left.

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 is very sound to make the cyborg cockroach turn in place and negotiate 90 degree 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 groun truth in Fig 19. The ground truth was taken from manually marking the cockroach position in the video frames.

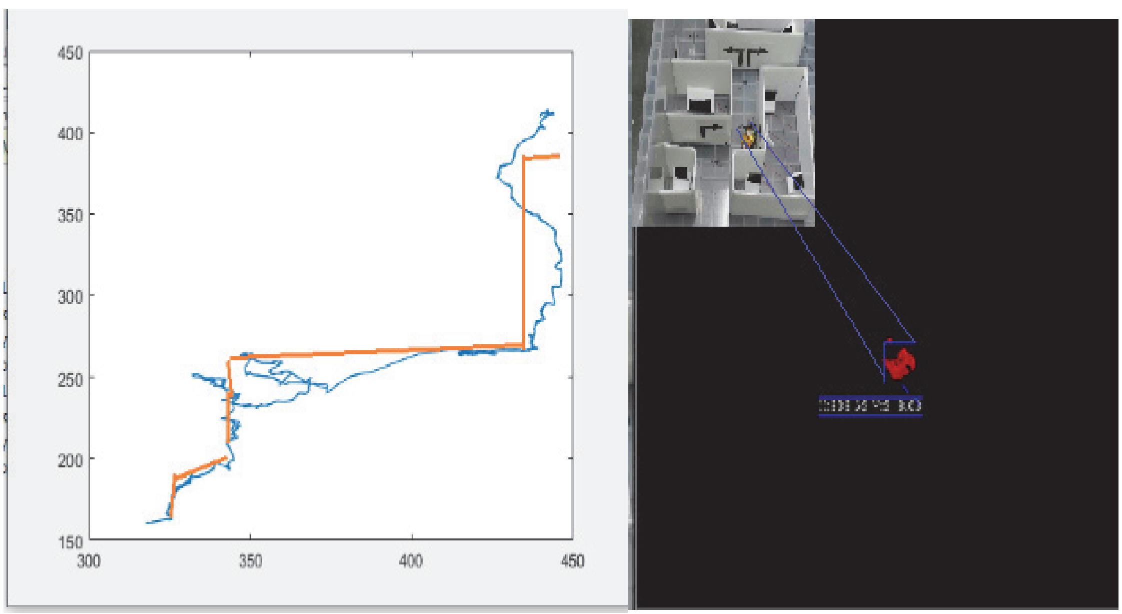


Figure 19: (Left)Path of the cockroach as tracked by camera, blue path is tracked with pixel error and orange path is ground truth. X-Y axis are the camera axis in pixels. (Right) Cockroach tracked after applying filters.

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 or importance because when it comes to urban search and rescue it would be possible to quickly 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 [38]. 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 25m, we would get still image at 640 x480 resolution but we would get 3 fps at 320x240. We tabulated our results in Table V. 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.

TABLE IV. CAMERAROACH DSTANCE VS FRAME RATE WIFI TESTS

No.	**CameraRoach WiFi Range test of camera**			
	Distance	***Stimulation signal***	***Resolution***	***Frame rate (FPS)***
1	10m	ON	640x480	6.1
2	15m	ON	320x240	6.1
3	20m	ON	320x240	6.1
4	25m	ON	640x480	Still image
5	30m	ON	160x120	3
6	35m	ON	160x120	1
7	40m	ON	160X120	0.3

Figure 20: Pictures captures at decreasing resolution starting from 640x 480 then 320x240 and last 160x120 at increasing distance from 10m,20m,40m during WiFi range test with the router.

Fig. 20 shows the decreasing resolution as mentioned in Table V during WiFi range tests. We used the Smart Mini portable router from GL-INET operating at 5v and max.1A 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 is useful when fitting through pipes and crevices. At range of 40m there is no possibility of first-person view with navigation control as live video fails, we can only grab still images at 40m but when it comes to closer distances like 30m slow navigation first person view control is possible and this is better at further low distances like 15m or 20m as first person view navigation has been tested to work. We also implemented Pivot turn feature where a small stimulation signal of 1ms makes the cockroach turn slightly by 10 degree towards the left or right where as the Beetle-Cam uses a miniature actuator arm for pivoting he camera. This would be useful to pan the camera when performing the operation of search.

This chapter describes a WiFi-enabled cyborg cockroach equipped with a wireless camera to send video telemetry feedback to the use/controller for search and rescue. We developed our own electronic hardware and software for the neural stimulation of the cockroach to make it navigate in a maze and send high-resolution wireless video feedback back to the user/controller for inspection or search and rescue. We describe our design of the cyborg cockroach, and present results of an evaluation experiment. We describe our unique electronic backpacks we developed for the cyborg insect which includes a GPS and a thermal camera.

give the implementation in Sec III, then the results in Sec IV and conclusion and future work in Sec V

2.6 Limitations

There are some limitations of the current system. The system should be custom engineered further to make it as light weight as possible to keep the centre of gravity low. What we have observed during some trials is that if the centre of gravity of the cockroach with the embedded system is high for certain obstacles like climbing over small pebbles the platform with the cockroach topples.

One more limitation that we observed is that the cockroach has a mind of its own and after some repeated stimulus though varying it ignores them and does its own random walk. This might help in wall following behaviour in some cases, but it is not possible to have a complete control over the mind of the cockroach for this on might have to give light sleep inducing medication to take more control over the cockroach brain. But the long term and a better solution is to develop an electromechanical equivalent of the cockroach in the form of its actuators, degrees of freedom of the leg. This will be lifetime problem to perfect it. Some interesting progress in this area has been in done in Harvard Wyss[37] institute called the Hamr micro robot that is cockroach scaled.

2.7 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 feed 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 [41]. 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 [32][33]. 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 [39][38]. NDB battery is a miniature diamond-based battery where a radioactive carbon-14 and resultant of the reaction is the flow of electrons which generates current and voltage difference. The NDB battery is compact, lightweight and has a long run time and thus is very much suited for cyborg insect application. By integrating GPS and thermal cameras with twin visual cameras is the first of its kind for cyborg insects especially in search and rescue scenario. The NDB battery can run for 10 of years and will not pose any radiation leak induced damage to the cockroach or people handling it because it comes enclosed in a radiation proof diamond which will absorb all the radiation. A cockroach can fit into smaller holes, where as a snake robot also is researched upon by several researcher to fit into tighter spaces like crevices. In the next chapter we will deal with how we can give a snake robot a sense of localizing sound to head help cries in a disaster scenario. We give a system level implementation to track sound only and show reactive snake robot gaits to this sound localization system.

3.Bio-Inspired sound reactive snake robot simulation

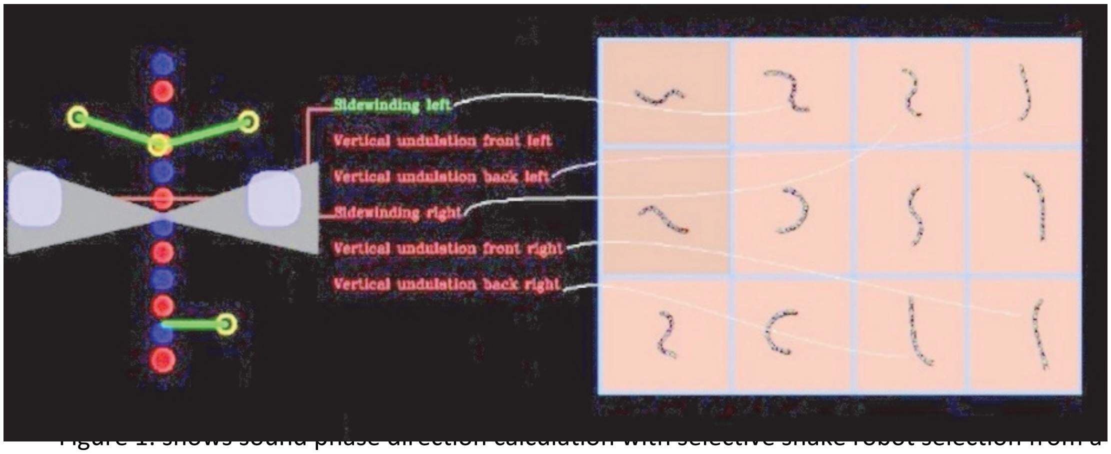


Figure 1: shows sound phase direction calculation with selective snake robot selection from a gait lookup table,

Figure 2: shows MEMs microphone array with sound source localizing done on an ARM microcontroller connected to the laptop via a USB-RS232 serial cable.

In this chapter we present a hardware (Fig 2) and software framework (Fig 1) in which we use the direction of the sound source to interact with the simulation of a snake robot with an intention to show survivor sound tracking capability in simulation. We present a gamification idea (like hide and seek) of how one can use the direction of the sound and develop interactive simulations in robotics and especially use the bio-inspired idea of a snake's reactive locomotion to sound. We use multiple microphones (Fig 3) and calculate the direction of sound coming from the sound source in near real-time and make the simulation respond to it. Since a biological snake moves away from a sound source when it senses vibrations, we bio-mimic this behavior in a simulated snake robot. This idea can be used for developing games that are reactive to multiple people interacting with a computer, based on sound direction input. This is a novel interface.

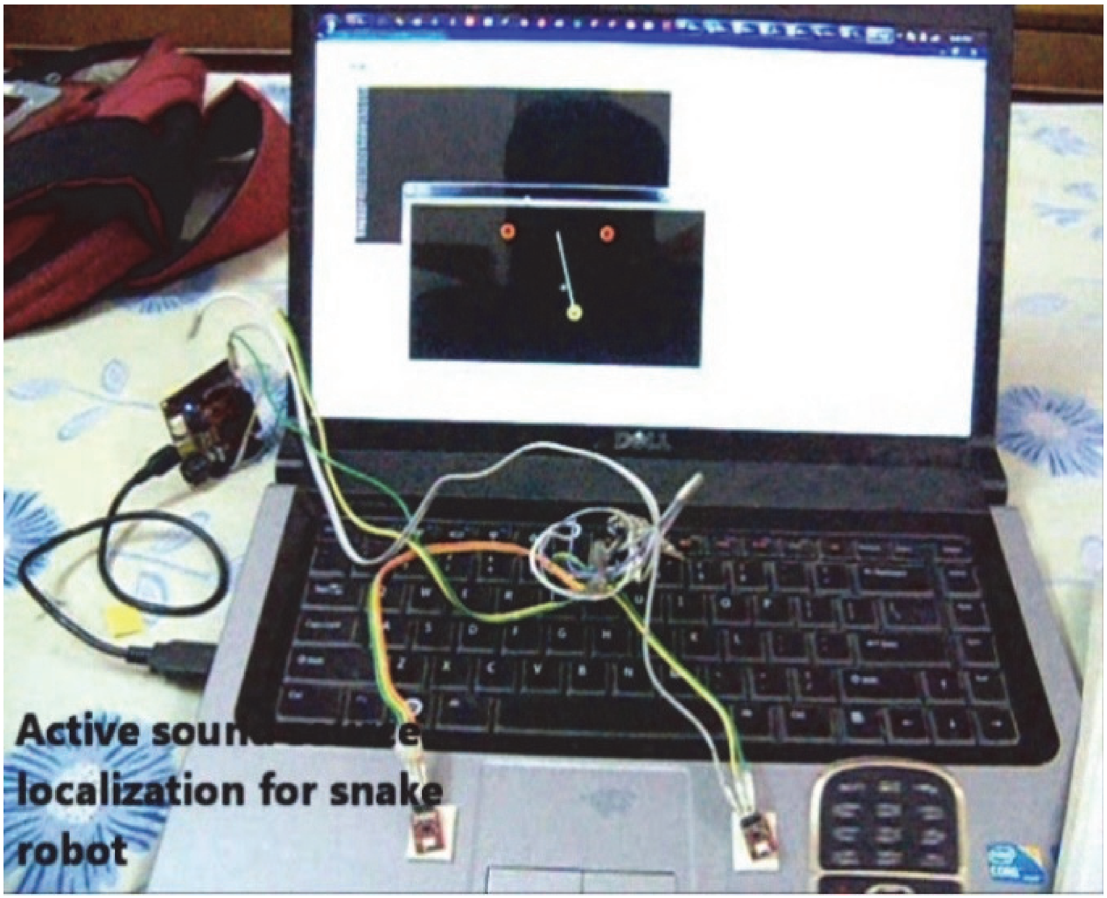


Figure 3: The above figure shows a pair of mems microphones connected to an ARM microcontroller and the ARM controller sends sound direction data to a laptop via a USB to a serial converter. The interface shown in the laptop points towards the source of the sound.

4.1 Introduction

There have been some applications of sound source localization in robotics where a robot is made to respond to audio stimulus coming from the person usually the sound source. For example, in a room, there is a robot and a person; when a person claps the robot orients itself towards the person. Or if multiple people are speaking and the robot shows that it is paying attention by orienting itself towards the sound source i.e a person. This has been tried in the humanoid robot Asimov in one of the demos that was developed by Honda [43]. In a particular application [44], the time of flight of the sound source in a snake robot was used to estimate its position in a pipe-like GPS denied environment. The snake robot was not only able to identify its location but also was able to construct a map of the surrounding environment. In search and rescue applications a cockroach was mounted with multiple omnidirectional and unidirectional mics to find out in which direction the help cries from people stuck under ~~the~~ debris in a disaster like situation were coming from and this information would be useful to first responders. It is widely believed that snakes cannot hear because they lack a visible ear on their head, but snakes have an inner ear with a functional cochlea [45]. They use this to detect the minute vibrations in the sand when prey is coming near. They not only hear as the prey approaches but also a snake's brain calculates the direction in which the prey is coming from. Sometimes snakes even avoid aerial predators like eagles or vultures by listening to the sound of the vulture and quickly go hide in their pit (Refer to the video at 2.02 where one can find this bio-mimicking behavior of a biological snake.)

So, we tried to develop a gamified interface based on this bioinspired idea of sound sensing by snakes. Another scientist Christian Christensen [46] a biologist from Aarhus University in Denmark attached electrodes to the snake's brain and found that the neural activity peaked when there was an auditory stimulus. They found out that the skull of the snake is very sensitive and can pick up vibrations caused by the sounds traveling in air. So that widely accepted myth that snakes are deaf is wrong and we thus want to use microphones in our snake robot and give it ears. The SITREC system [47] used in the TIM project developed new ways of game interaction with audio and this idea originated with the intent to make games for visually impaired and mainstream music entertainment. The paper [47] also mentions new ways of sound object design through spatial game soundtracks. Another paper describes the use of sound in audio role-playing games, in the project Kronos [48] and also discusses the sonic description of visual elements. We in this current snake robot sound project have also designed interfaces that have sonic audiovisual elements not only in 2D but also in 3D. This idea of sound source localization can be used in the future to make novel interfaces that interact with the position and direction of the sound. The underlying method of sound source localization has been a topic of study for a long time [49] and even in robotics, it is being researched [50]. However, this is the first time a snake virtual animation responsive to sound based on a bio inspired idea is being mimicked. The user can interact with the snake robot by using sound.

4.2 Description

In the initial experiments in calculating the direction of the sound, we used a single pair of microphones. We estimated the direction of the sound by estimating the time delay of arrival. Since sound travels in the air at a speed of 330m/s and if there is some minimum distance between a minimum of 2 microphones then the sound waves from the sound source depending on the position of the sound source arrive with a time gap. We cross-correlated both the time waves on a microcontroller after obtaining their respective patterns on the analog to digital converter and estimate the angle at which the sound source is present.

Figure 4: The top image shows a virtual humanoid looking in the direction of the sound. Here the sound source is a cellphone. The bottom shows our virtual humanoid.

We used this to make a virtual humanoid robot (Fig. 4) track and point towards the sound source and thus made a direction of sound interactive interface on the laptop. We used the same concept in a 4-microphone system where we put 4 mics on each corner of a rectangle and made a virtual snake robot move away from the source of the sound. Generally, it is observed that a biological snake detects vibrations it feels with its body coming from the ground and moves away from it to avoid a predator. We sensed the vibrations here in our experiment in the form of sound and bio mimicked the snake behavior in moving away from the predator sound source (Fig 5,6).

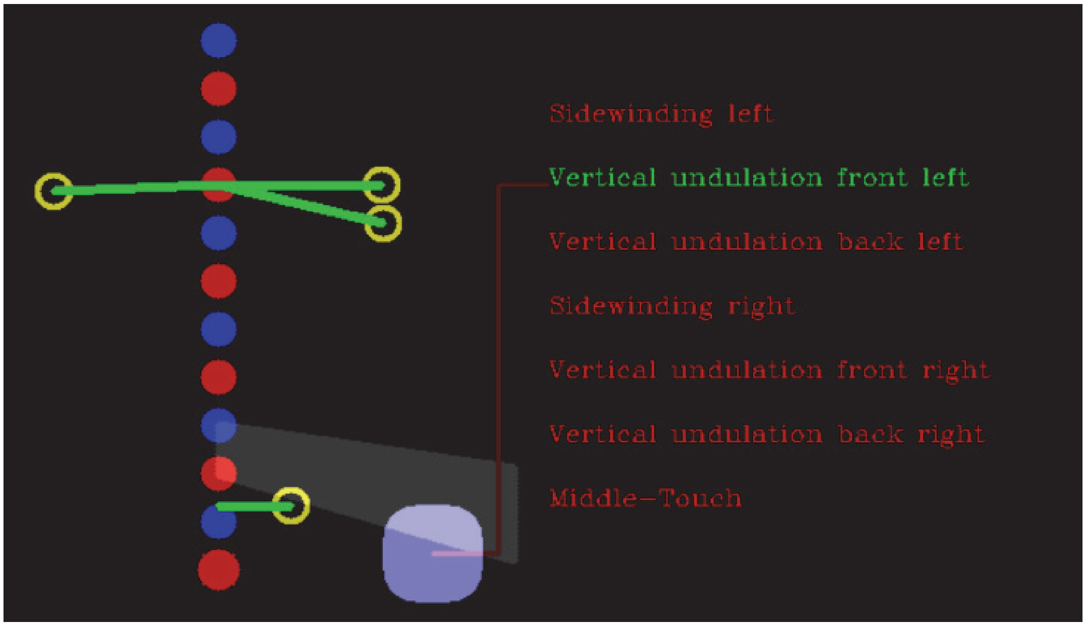


Figure 5: Figure showing interactive sound interface. The right side shows a lookup table to select the appropriate snake robot gait. The four green lines show the direction of sound estimated by the 4 pairs of mics. Each pair of mics is from the adjacent corners of the rectangle on which the mics are kept. The blue-grey colorations show the final direction of the sound source.

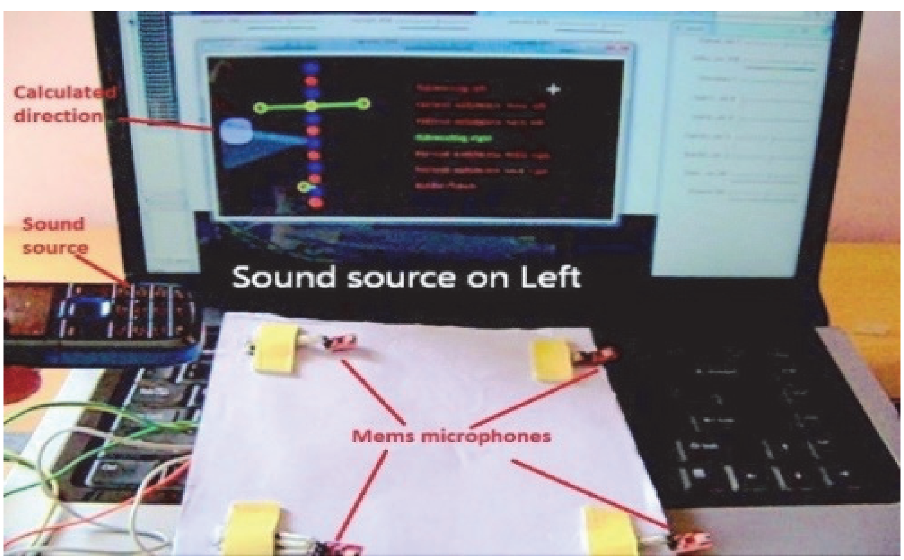


Figure 6: A 4 MEMs microphone system estimates the sound source direction in 2D. Here the pair of mutually perpendicular microphones give the ability to sense the sound along two axes (x and y)

We made an interactive sound interface using C and OpenCv graphic functions (Fig. 5) and also simulated the biological snake in a physics simulator. Depending on the location of the sound source we adjusted the gait parameters of the virtual snake robot (Fig. 7) and programmed it to move away from the source of the sound.

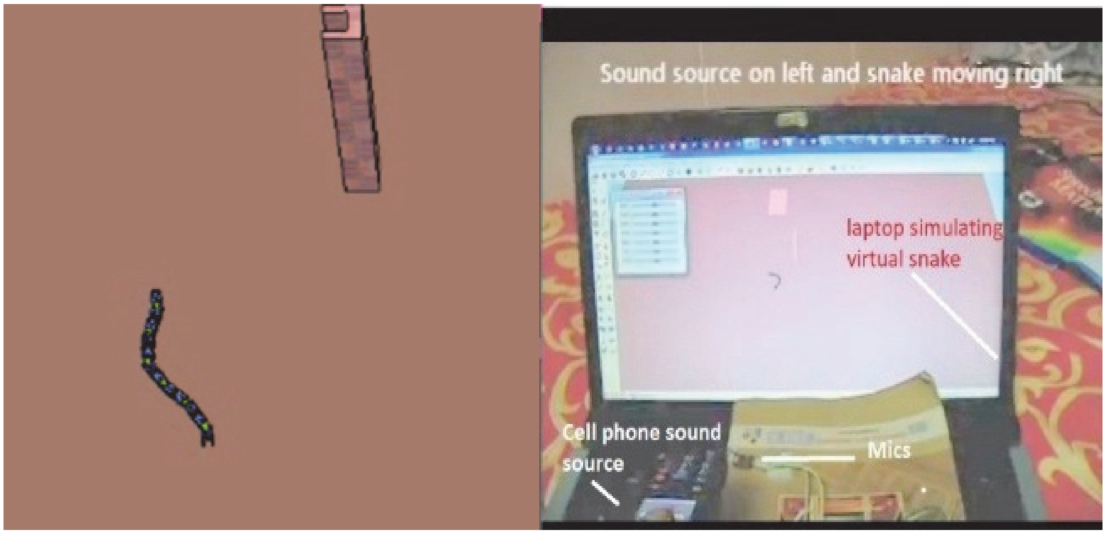


Figure 7: A simulated virtual snake robot with biomimetic behavior reactive to sound.

Since most of the cellphones, today come with two microphones or three we can calculate the direction of the sound coming from multiple speakers and use it to gamify recording apps and interfaces. This gamified interface relies on the direction of the sound source. The algorithm flow is as follows: capture microphone samples on multiple ADC ports in parallel for multiple microphones at minimum 100Khz and compute the cross correlation between ~~the~~ two or more microphone signals. A cross correlation is an expensive function, so we used a minimum of sum of least squares after a shift through the time axis of the captured array of microphone data

$sum[j] = sum[j] + ((a1[i + j - mid] - a2[i]) * (a1[i + j - mid] - a2[i]))$, *where a1 and a2[] represent captured mic data.*

There are some existing sound boards that do source localization that have been launched in ~~the~~ recent years that are used for Alexa like devices. But we developed this hardware architecture and embedded system in April 2011 even before Alexa was launched and it is much more cost effective as it uses an inexpensive Arduino based Maple-leaf ARM microcontroller and mems microphones. Nowadays most smartphones use 2 or more microphones, and we can create multi-user interactive sound direction-based games and apps like we have demonstrated in our work here using 2 mics, in addition with a virtual humanoid robot (Fig 4) and also for a virtual snake robot (Fig 7).

4.3 Future work

We also built a single snake robot module that has a microcontroller and mems microphones. We would like to build an entire snake robot and make it move relative to the sound coming from a sound source. We also want to try the anti-biomimetic idea where instead of the snake robot moving away from the sound source like a biological snake, we would instead make it move towards the source of sound so that it can be used in search and rescue scenarios to find people trapped under debris. We show how a snake robot with shape reconfiguration can track a sound source like the help cries of survivors in a rescue scenario.

4.Sound source localization through shape configuration of a snake robot

This chapter describes a snake robot system that uses sound source localization. We show in this paper as to how we can localize a sound source in 3D and solve the classic forward backward problem in sound source localization using minimum number of audio sensors by using the multiple degrees of freedom of the snake robot. We describe the hardware and software architecture of the robot and show the results of several sound tracking experiments we did with our snake robot. We also present biologically inspired sound tracking behaviour in different postures of a biological snake robot as "Digital Snake Charming".

5.1 Introduction

Sound source localization problem is a classic problem and many robots in the past have tried to implement SSL (sound source localization) in their architecture. Mostly if it is a humanoid robot then they used binaural hearing and in case of some other robots like UAVs, mobile robots etc they have used an array of 4 or more microphones. The idea was to localize a sound source using either binaural method with HRTF (head related transfer function) using ILD(interaural level difference) or IPD(interaural phase difference) and TDOA (time delay of arrival method). We here present our attempt to do SSL in a hyper-redundant snake robot. Till today there have been no snake robots which use microphones to bio-mimic the biological snake and explore its sound reactive behaviours. Snake charmers in India have been demoing this ability in street shows with biological snakes where they blow a musical instrument called "Pungi" (fig.1) to raise the attention of the snake so that it raises its hood and tracks this sound. Here we have studied different sound source localization works done in the past, the use of array of microphones on robots and we tried to implement for the first-time sound source localization with tracking based biomimicking behaviour and localize a sound source through reorganization of the hyper redundant structure of the snake robot using minimum number of microphones. We also coin the term "Digital Snake charming" to show this behaviour.

We also show how forward-backward problem in SSL is solved using our snake robot. Nobody did sound source localization on a snake robot before and gave snake robot a perception that is auditory in nature. Giving sound perception to snake robot not only solves the sound source localization problem in a resource efficient manner but also opens new interesting sound tracking behaviours as seen in real snakes. We solve the forward backward problem by getting the snake robot into a piecewise gait posture and make it scan 360 degrees with its change of posture and solve localization problem, the forward backward problem and show biomimicking behaviours. Right now, tracking multiple sound sources is out of the scope of this paper, that in itself is a different problem. In some humanoids this was possible before with pinnae like ear structures and was not very accurate, we are +/-5 degrees accurate in our solution. The paper demonstrates this in the form of a system design, software and mechanically built solution. Forward backward problem which is commonly solved using pinnae shaped sound receivers in some papers and naturally in humans where the ears are shape so is solved here in using pose reconfiguration using minimum microphones (mics) in L shape. Earlier works required 4 or 8 or 12 localization mics but our strategy to localize the sound source works with a minimum of 3 microphones through shape reconfiguration to L shape along the 4 quadrants.

Snake robots have been widely researched by CMU Biorobotics, Howie Choset [69,70], Shigeo Hirose[72] from Ti-Tech, EPFL[71] etc showcasing their capability to do all terrain locomotion both on land with rocky environments, through tight space like fitting through pipes and crevices and also swim in water. Our idea in this paper is to fit the snake robot with microphones so that we can listen for sound of the trapped survivors in a disaster scenario and get a location information as to where the sound is coming from. This we believe will help in search process of a search and rescue scenario and thus help locate survivors faster.

5.2 Related work

We discuss about binaural array and multiple array microphone systems. We discuss about their computational aspects of sound source localization. Then we outline references of papers which used sound source localization in robots. We also discuss how sound source localization problem evolved over the years and some classical problems in localization like the forward-backward problem for which we provided a solution using a snake robot (fig.2) in this paper.

5.2.1 Binaural and Multiarray microphone based localization

Jean M.V et al[51] discuss two robots Robita and SIG humanoid where two stereo microphones have been used. One pair is for capturing external sound and the other is for capturing internal noise because of motors of the humanoid. They say it is difficult to match human hearing because we have a shadowing effect because of our ear structure. So, they used an 8 array microphone system on a pioneer robot to localize in 360 degrees. Another paper by Inkyu[52] et al mentions about microphones arranged in the form of a cube. Generally to be able to compute time delay of arrival to calculate the sound source direction one needs more than a single frame of data but here they were able to take a single frame of sound, used a reflection aware setup so that the reflected wave of sound is generated and is traced back from the cube of microphone array to get the sound source location in 3D. Shengkui [53] et al mentioned their 8 microphone array sound source localization implementation on Olivia robot which enables the robot to face/orient towards the face of the speaker even if the user is out of the field of vision of the camera and even in poor lighting conditions. This is one advantage of using audio perception for search and rescue robots like in our snake robot because under poor lighting conditions also we can detect a sound source which could be the help cry of a possible survivor. Their robot HARK uses 8 microphone robot audition system using steered beam forming. Some humanoid robots like HRP-2 combine both audio and vision to detect speech events from vision. Another paper by DeForge[54] discusses about sound source localization using software-based mapping of high dimensional interaural data. Interaural level difference and interaural audio differences using head related transfer function has been one of the most famous methods to localize sound sources in humanoid robots. Hong[55] et al mentions in his paper that in 2006 Honda performed multi source real time tracking by embedding 64 microphones in the room and 8 microphones in the robot’s head. 8 number of microphones appears to be a popular choice for many SSL systems but in resource limited application or damage to the robot we show how the same can be achieved using 2 or 3 microphones but with the help of multiple degrees of freedom configuration of our snake robot in this paper. Another implementation was from Canada in 2007 where they used beam forming on a robot with 8 microphones to avoid obstacles. Hara in 2008 says 8 channel microphones had better localization accuracy in REEM-A humanoid. Daniele [56] et al mentions his work on using 4 array microphones in his multi rotor UAV with beam forming based acoustic source localization. The idea was to suppress the noise in audio due to rotors and get sound localization information of point of interest. This paper [57] presents a micro phone array design and how they optimize it for beam forming purpose. The microphone array here has 64 microphones arranged in the shape of a sphere with 350mm diameter designed to be mounted on a mobile robot with omni directional sensitivity in azimuth and elevation. They have tested the microphone array in challenging environments and with different pressure sound sources and have provided their results. The performance of beam forming improves with the increase in the number of microphones and even their robustness to different pressure sound sources increases. In the paper [58] for generating the training data set the robot HEARBO used an audio setup which was equipped with 8 and 16 channel microphone arrays. A 7 channel Microcone microphone array was also used to get the impulse responses.

5.2.2 Search and Rescue snake robot systems

Search and Rescue and inspection go hand in hand where one has to search through tight spaces using a camera. In the paper by Yoshiaki [60] et al they mention about inspecting a pipe and generating maps using ultrasound. At the opening of the pipe these is a speaker and in the head of the snake there is a microphone. The snake also has an IMU, by knowing the time of flight and length of the path taken by the sound the snake robot is able to generate a map in the GPS denied pipe, it is to be noted that this is not SSL. Odometry in pipe like environment is also not accurate due to slippage. The accuracy of map generated was more than 68 percent here by snake robot using sound based online localization method. Snake robots are especially suitable for moving in pipe like environment because they can twist their multiple DOFs and generate a pipe climbing gait. P. Thanu [61] et al says that Search and rescue robots these days as the demand need to be fitted with advanced sensors, reliable communication equipment so that they can help the rescue workers in rescuing survivors buried under the debris. USAR (urban search and rescue) typically has a dynamic environment, and the robots need to have a sense of sovereignty to cope with the dynamic conditions. The snake robot by Dr.Gavin miller uses infrared range finding sensors, camera and flex sensors to sense its environment. Hummingbird is an advanced intelligent UAV developed at University of Oxford that has a camera and works in an autonomous way. The USAR robots need to have features like reconnaissance, search functions, rubble removal and victim extraction and telepresence. This paper also presents a survey of human detecting sensors like Binary sensors, SpO2 sensors, CO2 sensors, thermal sensors, sound sensors like microphones, thermo piles, vision sensors and radio etc. The robots need to have a secure and low energy consuming/ energy efficient wireless network communication equipment. Generally, when the robot goes out of the sight of the operator their location is lost but by using Zigbee sensors networks and other sensing modalities for wireless networks like signal strength and 4G we can get location information of the robot. Target tracking is one of the important features discussed in this paper which is of value in USAR scenarios. In the chapter from a book by Fumitoshi [62] et al they discuss about both wheeled and non-wheeled snake robots they developed for inspection of narrow crevices of buildings and insides and outsides of the pipes. So, snake robot especially finds application to fit through tight spaces as it can change its degrees of freedom and when it comes to narrow spaces in an urban search and rescue situation, it is an important application for snake robots. So, our idea is to combine the ability of sound-based localization and use it in snake robots for the future purpose of search and rescue, the first step towards this task we identified is to equip the snake robot with microphones and study various possible biological, bio mimicking and anti-biological behaviours.

5.2.3 More sound localization works

Kazuhiro[63] et al in paper says that in the real word when capturing audio data there will be many sources of noise in the environment, reverberations and noise from the motors of the robot. This paper uses active direction pass filter, interaural phase difference, interaural intensity difference to localize the sound. Human tracking and sound source localization is implemented here in this paper in the upper torso of a humanoid robot. Yosuke[64] et al in their paper mentions that localization was implemented in the humanoid robot Robita. Here microphones have been arranged on a 2DOF head neck. Here stop-look-act form of tracking is implemented. This is one of the seminal works in which sound localization system using binaural audio has been setup on a 2DOF movable head neck system. Sound direction here is estimated using spectral properties and HRTFs. Francois et at [65] says that sound localization becomes difficult where there are noise sources in the environment. It is difficult to estimate the direction from where the sound is coming from the intended source when there is noise. So, this paper describes a binary weighted frequency mask on generalized cross correlation with phase transform. We in our Snake robot Z3(fig.1) use a Fast Fourier transform in our detection system that differentiates between predator sound and sound from prey and uses this frequency domain info in multiple sound source tracking and invoking the appropriate gait behaviour in moving the snake robot. SSL can be used to give the location and number of sound sources which later can be used for sound separation. Nakamura [66] et al says singular eigen vector decomposition methods have been used earlier but its performance can be improved against noise and high power using generalized eigen vector decomposition. John C Murray [67] et al in their paper describes a sound localization system which uses only 2 microphone to closely replicate the mammalian hearing system. They also used audio cues to help in localization. Mammals can sound localize with an angular resolution of 1 deg and azimuthal resolution of 5 degrees. This is because the audio cues like interaural time difference (ITD) and interaural phase difference (IPD) are encoded in the lower brain stem regions. A multi-processing model has been used to do the sound tracking here. We in our snake robot use different processing pipelines for gait, sound localization and IMU heading calculation to achieve better sound localization performance. Looking at all this we chose minimum mic configuration and used near real time cross-correlation method to sample and estimate the global minima to find the sound source. Xavier [68] et al discusses about non arbitrary shapes to do sound source localization using time delay of arrival estimate. But none of these papers show if by changing multiple degree of freedom where the microphone's geometric positioning is reconfigured to get a better estimate of the sound sources position or direction and thus the localization. This is especially of good value as snake robots are multi DOF reconfigurable. Their geometric analysis helps in determining a position of mics in geometric space with global optimization that corresponds to the sound source being localized. Such TDOAs determined are called feasible sets which correspond to a unique positioning in the source space.

Figure 1: This is a musical instrument call the Pungi used by the Snake charmers in India.

5.3 System Description

5.3.1 Hardware description

The snake robot Z3(Fig 2.a, Fig 2.b, Fig5 shows hardware schema) consists of 12 servo motor modules using high torque HiTech7995 TG 34kg-cm motors. Each motor under loaded condition can consume a total current of 3.5A. The 12 modules are linked successively with each other in an orthogonal fashion. The linkage is done through custom made servo brackets using aluminium sheets through sheet medal bending. Before the sheet metal bending process, the footprint of the bracket is made using a CNC machine. As they are orthogonally linked, 6 servo modules have their axes parallel to the ground and the rest of the 6 servo modules have their axis parallel to each other by perpendicular to ground. This way a 3D skeletal structure of the snake robot was built. After this the modules are covered with foam rubber adhesive skin. The foam rubber skin helps in giving traction from ground to the snake robot and also helps in absorbing the impact when the snake locomotes on the ground. A 40A 7.4V adjustable power supply is use. Under different postures of the snake robot, we observed a maximum current between 5A to 10A for gaits like caterpillar crawling and holding a static position in raised hood mode. The servos are analog that means they cannot be networked onto a single BUS like RS-485 or TTL. The reason we chose analog servos is because if we use networked servos like Dynamixels from Bioloid company we observed that there is bus delay in servo command packet transmission and only one servo can be commanded at an instant, whereas in analog servos all the servos can be simultaneously controlled at a time using pulse width modulated signal on each port pin of the microcontroller. The microcontroller used is Teensy 3.2 Arduino. We are using an inertial measurement unit in the head to get the absolute pose estimate of the robot. We know the commanded angle of each servo arm (eventually each servo without a mechanical obstruction almost reaches the commanded position with a back lash error in servo output shaft and skeletal structure) and this relative to the head we will know the angular position of each of the module and thus the entire pose of the snake robot can be estimated. The IMU is connected over the I2C bus to the microcontroller. There are 2 pairs of MEMS microphones in the head and there are 3 microphones along the middle of the body of the snake robot. We are also using a Zigbee module in the head of the snake robot and one receiver module at the laptop computer end. Zigbee's use will be described in the follow section. The micro-controller and the microphones are powered using an off the shelf DC-DC buck which reduces the input voltage from 7.4V to 3.3V which is the compatible voltage for the MEMs mics, microcontroller board and Zigbee.

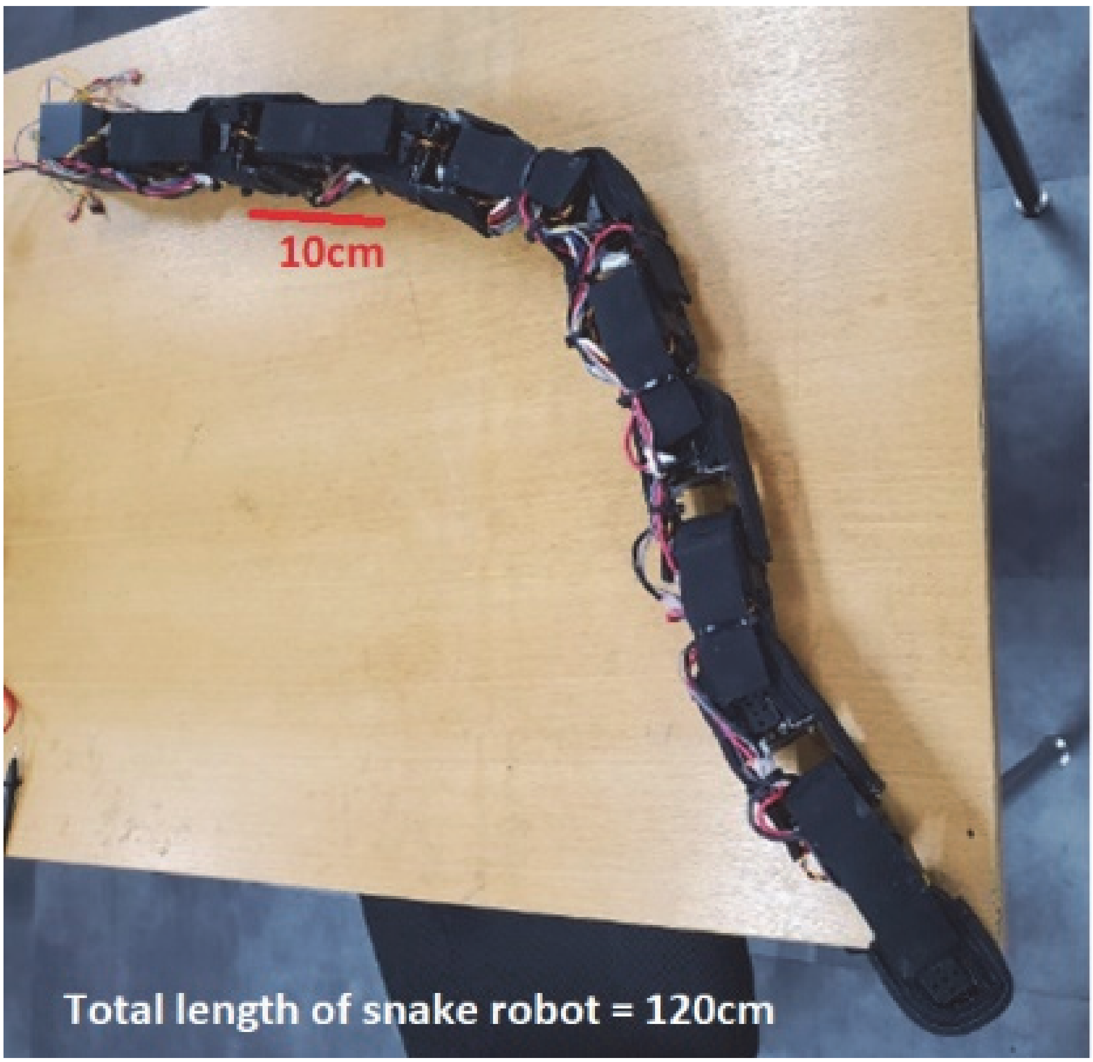


Figure 2.a: Snake robot Z3 with foam adhesive skin

Figure 2.a: Snake robot Z3 with foam adhesive skin

The head of the snake robot was 3D printed(fig.4). An IMU was assembled on the top of the head along with 4 mics on the top, bottom, left and right faces each of the 3D printed cube. The mics were assembled such that the glue which holds the mics to the face does not dampen the sensitivity of the MEMs mics. Earlier we noticed that gluing directly at the back of the MEMs mic PCB reduced the sensitivity to 1/10th. So, we just glued at the point of the signal wires to the mic so that the microphone is left free to vibrate like how human ear drum is left free to vibrate by its biological design. These are omnidirectional mics and thus no sound shadowing effects like human ears were there to be taken advantage off. All the wires going into the head of the robot can be seen as like nerves of human body converging into the head from the neck and below.

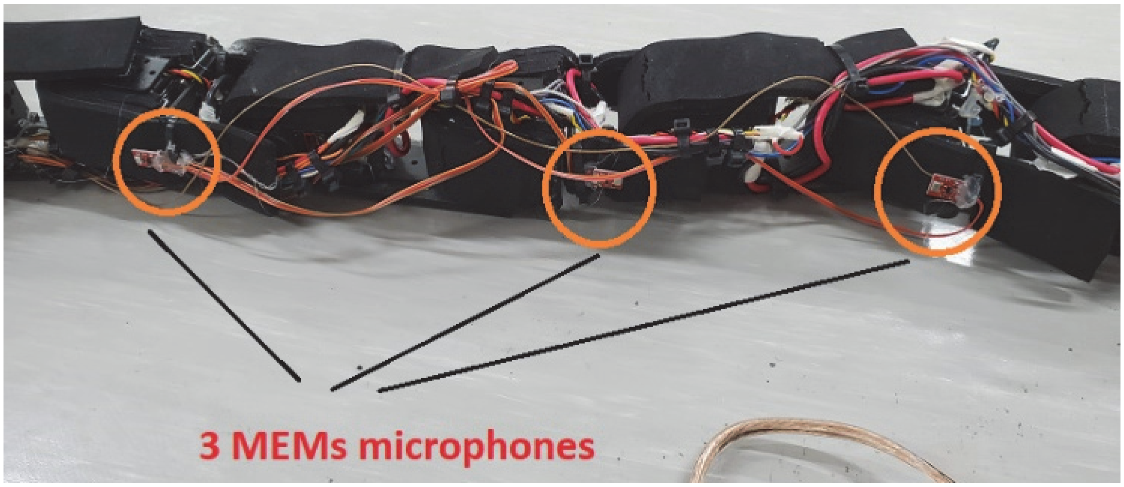


Figure 3: 3 MEMs microphones the only ones used for 360 localization and forward backward problem.

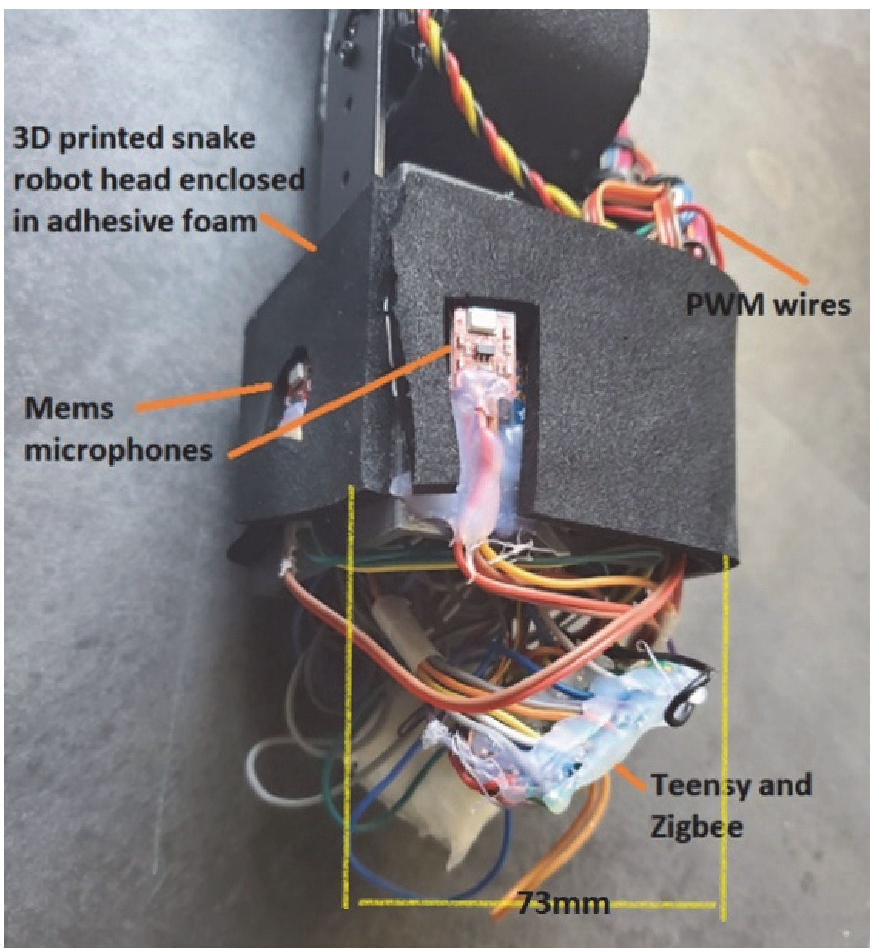


Figure 4: Head module of the snake robot.

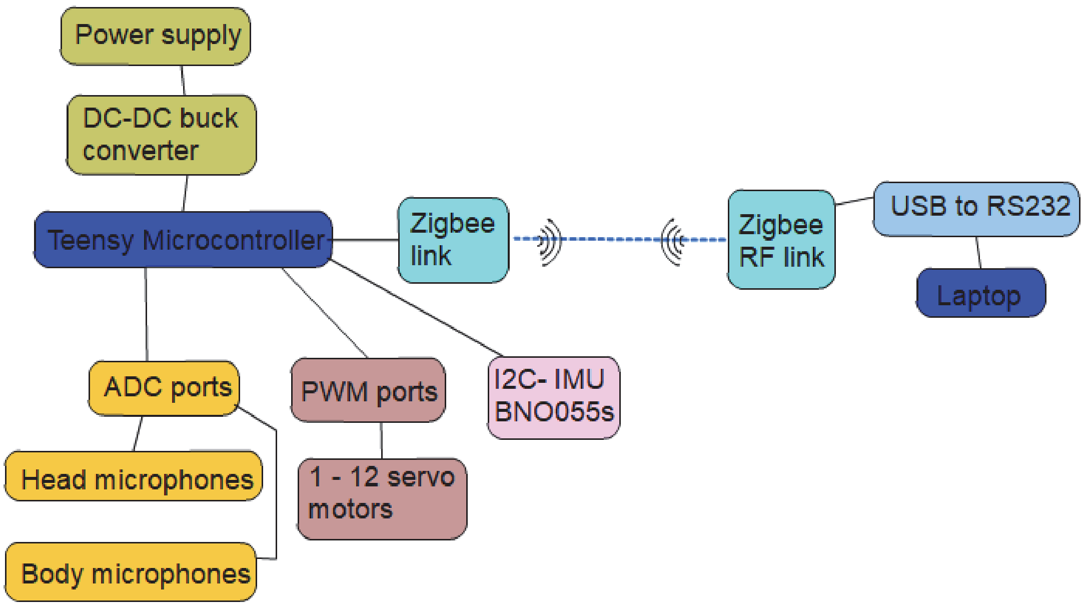


Figure 5: Hardware Schematic

We use 3 MEMs microphones (Fig 3) on the middle portion of the body of the snake robot used for 360-degree localization of the sound source. The hardware section has two parts. One on the laptop end and the other on snake robot both are connected by the ZigBee wireless link. On the snake robot the microcontroller received head and body microphone signal over the analog to digital conversion ports. It generates pulse width modulated signal for controlling the posture configuration of the servo motors in the snake robot. It reads IMU data over I2C. The laptop receives localization calculated onboard the snake robot and inertial measurement unit (IMU) posture data for the visualization.

5.3.2 Software description

The snake robot has some functional modules running in the firmware that sits inside the Teensy microcontroller. All the computation runs onboard the snake robot head unlike our earlier snake robots (Snake P3[9]) whose gaits were calculated remotely on a computer and sent to the snake robot controller wirelessly. One sub routine is the sensory perception layer which gather MEMS microphone audio data from all the 7 microphones on individual analog to digital converter ports. This sensory layer also gets head orientation from the IMU so that the posture of the snake can be mapped. There is a sound source localization module function which calculates the direction of the sound coming from a pair of microphones each. The sound localization module uses cross correlation function which runs at 50Hz. The localization data coming from the pair of microphones are interpolated to get an actual and a valid location of the sound source relative to the position and orientation of the snake robot. We have also coded two Kalman filters one for each pair of microphones along the X axis and Y axis.

Here is the pseudo code for the 1-Dimensional Kalman filter.

```
mea3 = micpos3;
kalman_gain3 = err_estimate3/(err_estimate3 + err_measure3);
current_estimate3 = last_estimate3 + kalman_gain3 * (mea3 - last_estimate3);
err_estimate3 =  (1.0 - kalman_gain3)*err_estimate3 + fabs(last_estimate3-current_estimate3)*q3;
last_estimate3=current_estimate3;
micpos3k =  current_estimate3;
```

“micpos3” is the initial microphone pair localization value. “micpos3k” is the estimate value after the 1D Kalman filter is applied. This value is robust to noise and jitter in the microphone signal. We also use a threshold filter at the ADC to prevent false noise capture leading to ambiguous localization values. err_estimate is the average error calculated after applying the Kalman gain.

Another routine captures microphone samples on multiple ADC ports in parallel for multiple microphones at minimum 100Khz. Then we compute cross correlation between the two microphone signals. Now cross correlation is an expensive function so we used minimum of sum of least squares after shift through time axis of the captured array of microphone data

*sum[j] = sum[j] + ((a1[i + j - mid] – a2[i]) * (a1[i + j - mid] – a2[i])), where a1 and a2[] represent captured mic data.*

A pair of Zigbee modules is used to communicate between the snake robot and the laptop computer. Over this wireless link we send information like computed sound localization values, head IMU yaw, pitch, and roll values so that we can use this to update our remote visualization user interface software. We also send some condition flags to update the pose of the robot and sound source detection confirmation flags as well.

We also use a FFT (fast Fourier transform) filter to eliminate other environmental noise sources but detect only the human sound through the way of bandpass FFT. Fig 6 shows two software sections. One on the laptop which has USB to serial parsing block. Snake posture and sound localization mapping and another program to generate sinusoidal sound for the sound source. On the snake robot the Teensy microcontroller has software blocks for Cross correlation. Kalman filter, snake robot posture code and sound tracking functional blocks.

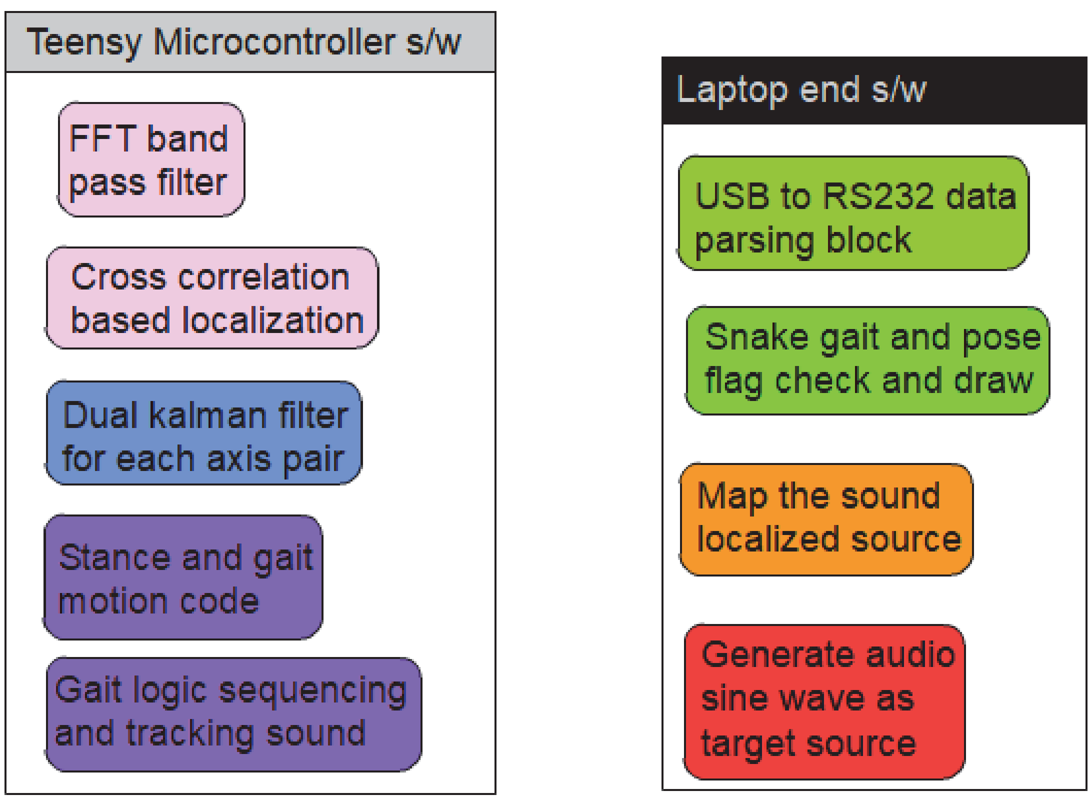


Figure 6: Software schema

5.3 Experiments and results

5.3.1 Digital Snake Charming/ Head tracking

Biological snakes like the "Ophiophagus Hannah- King cobra" snake exhibits locking and tracking a particular object of interest or danger through vision and sound. Snake charmer's always use this to raise the attention of the snake using their musical instrument Pungi. We bio-mimic this and show digital form of snake charming here called "Digital Snake charming". Christian Christensen [73] a biologist from Aarhus University in Denmark attached electrodes to the snake's brain and found that the neural activity peaked when there was an auditory stimulus. They found out that the skull of the snake is very sensitive and can pick up vibrations caused by the sounds traveling in air. So that widely accepted myth that snakes are deaf is wrong and we thus want to use microphones in our snake robot and give it ears.

Earlier it was thought that the biological snakes do not have ears and thus cannot sense sounds but can sense vibrations with their bodies coming from the ground. But a recent work shows that the snake behind their head have an auditory sensory system that are like ears hidden under the skin on either side of their head. So potentially they can track sounds as well. To mimic this capability, we have equipped the snake robot's head with 4 microphones arranged with a phase gap of 90 degree. This gives our snake robot the ability to track the sounds and follow the target by swaying its head in 3D (fig.7 and fig.8).

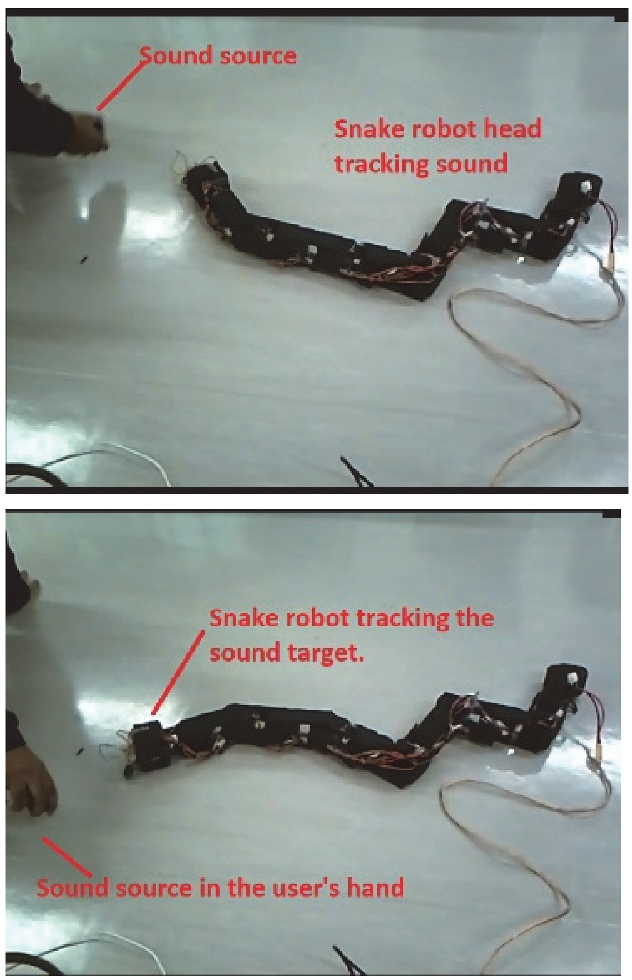


Figure 7: Snake robot first half of the body tracking the sound source in user's hand. The sound source is a Bluetooth speaker playing a sinusoidal sound waveform.

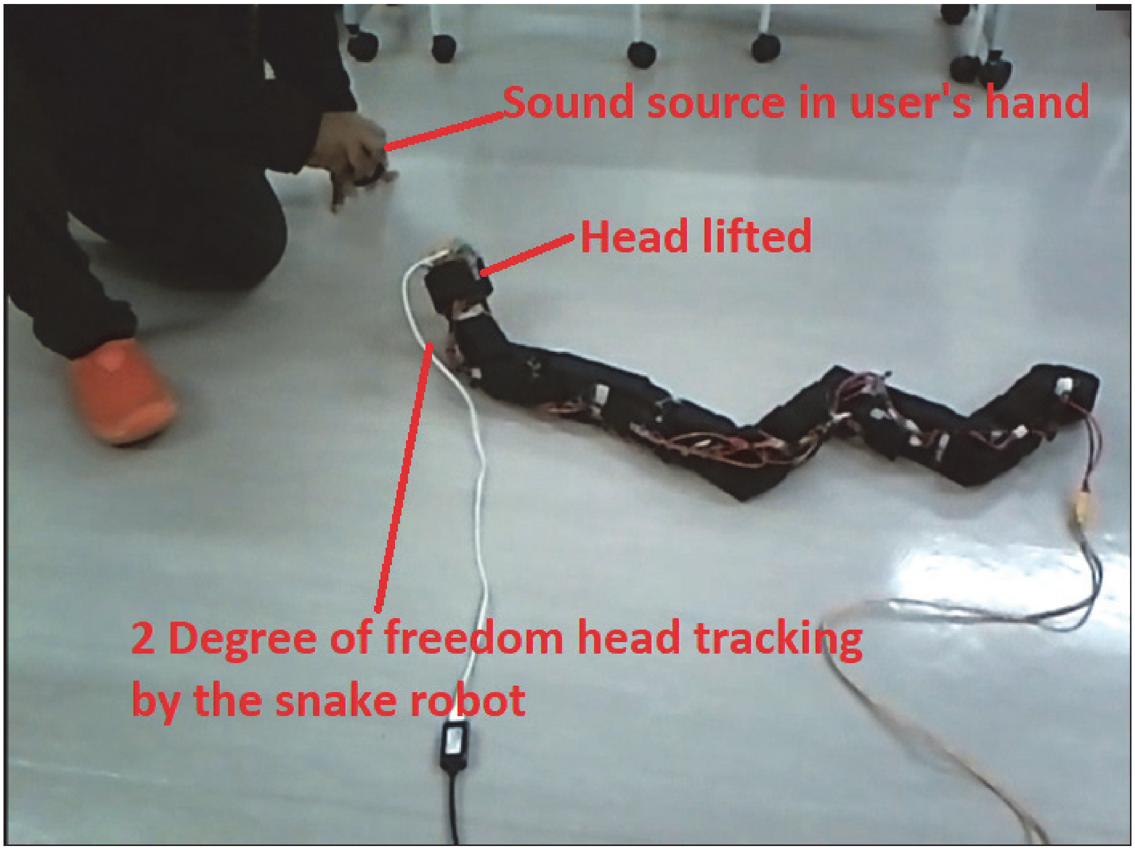


Figure 8: Head lift and track by snake robot with sound source in user's hand.

5.3.2 Hood raise and track

In this mode the snake robot takes a stance like the biological "Ophiophagus Hannah-king cobra" snake and tracks the auditory target. In this mode balancing the weight of the portion of the body is difficult and so we had to vary the link lengths that raises above the ground and take a backward stand such that weight of the raised portion is supported by the curled tail on the ground. Even the real biological cobra snake takes support from the curled part of its body and the tail to raise its hood (Fig 9).

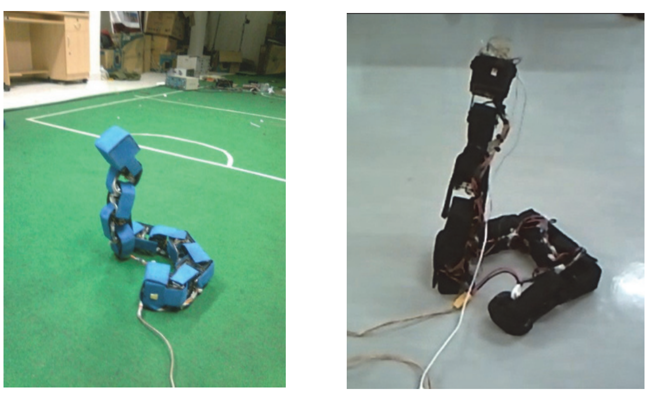


Figure 9: Hood raise posture of Snake P3[9] (left) and Hood raise for Snake Z3 (right) and listen to sound source.

5.3.3 Snooping

The biological snake always does not take a raised hood stance. It takes a raised hood stance when it wants to warn the human or animal that is trying to cause it harm. Sometimes the snake only lifts a part of its body and looks around generally when the snake is on the move and exploring. This is the classing snooping action which was also integrate a hybrid snake-wheeled robot for the purpose of search and rescue where the wheeled portion of the robot goes to a target site and the snake arm tried to look for objects of interest with a camera. But we have integrated a audio snooping capability in our snake robot where a part of the body is above the ground in the air and the rest of the part is curled in a zig zag /half rounded fashion to get some support(fig.10). The footprint is maintained during the posture transition in one half of the snake robot's body to avoid flipping or rolling on one axis.

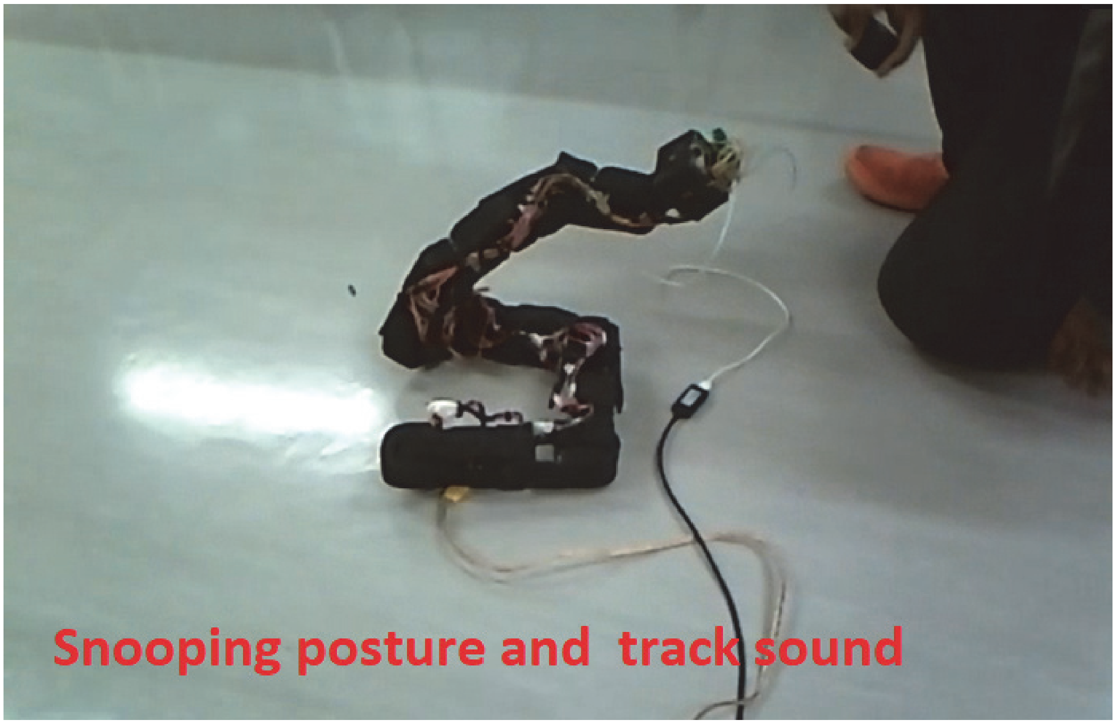


Figure 10: Snake tail curl and half body lifted above the ground like a snooping posture and track sound. The snake robot can also lift its tail and get into a rattle position but still track the sound in 3D.

Due to one particular coding error in sound tracking to invoke the gait we observed the snake robot would move in unpredicted and random ways and it appeared as if a real biological snake is being handled by a person.

5.3.4 Track and Move

In this mode of gait, the snake robot loops in cycles to scan for auditory source with its head and then curve its body appropriately to trace a curved path. The direction of motion is governed by the curvature of the snake's skeletal body which is formed by the servos with their axis perpendicular to the ground termed vertical servos. The horizontal servos (which are the servos whose axis of rotation is parallel to the ground) execute a differential curve namely the caterpillar [84] gait here. This motion scenario is as if the snake robot is searching for prey/survivor in a search and rescue scenario and senses the sound and then moves towards it. Such behaviour has been observed in biological snake. Here in our snake robot, we use stop-hear-act approach as seen in some animals like squirrels etc. Stop-hear-act allows us not only to eliminate motor noise but to also get the stance of the snake robot like the raised hood position of a biological snake to listen to the sound, we also turn the motors at low speed.

5.3.5 Localization through shape reconfiguration

Here is the idea behind designing the snake robot with microphones. Generally, if one uses two omnidirectional microphones then one can use Time delay of arrival and localize along on axis only. But if the object is above or below the line joining the two mics then one cannot differentiate if the source of sound is above or below that line. This is called the classical forward-backward problem in sound source localization. Some have increased the number of mics to 4 or more like have provided an array of mics along the 3 axis to solve this problem, some researchers have made the mic directional using pinnae (ear like structures), some have used directional microphones etc. For this differentiation we need to add a 3rd mic that is along the perpendicular to the line joining the two mics, but the problem is we cannot identify all the four quadrants or in 3D with just 3 mics, we will need 4 or more to achieve better localization accuracy. We mitigate this problem by using only 3 mics but since the snake robot is a hyper redundant structure and has the advantage that its degree of freedom can be controlled, we used this strategy. This solution uses the snake robot's mechanism as an advantage to minimize the mics. Compared to wheeled robots it is difficult to estimate the position kinematically and predict its position after some gait execution because like all other non-wheeled snake robots this robot also slips. If is a wheeled robots it is possible to roughly estimate its position with the use of encoders indoors or use SLAM based navigation, but it is not possible to mount some sort of encoding sensors on snake robot to estimate its slippage. However, if used outdoors the snake robots' position can be estimated using GPS and relative posture of its body can be estimated using servo encoders (not wheeled encoders) and indoors if we use optical motion tracking system or external camera-based tracking system it is possible. SLAM based navigation might also be possible on the snake robot but SLAM for snake robot is out of the scope of this paper. We can get the snake posture information from the IMU in the head and in the L shape the snake other half of the body is almost 90 degrees to the first half. So even though there is slippage and snake position information in world frame is erroneous, the posture information can be estimated well with relative angles of the snake servo modules thus its body in the world frame and then the sound source localization with respect to the revised posture of the snake body can be found. Here we estimate the global pose of its head using IMU and snake relative pose of its successive modules using motion commands. Use of onboard encoders in the servo modules or the use of smart servo modules will give more accurate posture information, but it is not needed for the current sound source localization application. The idea is we roughly need to get the snake form an L shape and make this L shape rotate in 360 degrees to calculation localization information as it undulates out of L shape to line shape and gets back to L shape (Fig 11, Fig 12 and Fig 13, Fig 14).

The key idea is to place one mic in the middle of the snake robot's body which becomes the origin and orient the other two mics one each along X axis and Y axis. To align these mics along these axes we pivot the body about the origin mic module and then make an L shape with each mic on one each of the two legs of L shape. Then we do cross correlation based TDOA estimation. Then the snake robot is commanded to form a straight line which is the normal shape. By this time the snake robot would have rotated by 60-90 degrees on the ground. The exact angle by which the snake robot's body has turned cannot be told accurately in world reference frame because of slippage and backlash however a rough estimate can be done using the IMU in the head. Then the robot is commanded again to form an L shape and localize. The transition from one L shaped posture to another L shape postured which is expected to cover another quadrant is also not perfect because of slippage and lack of snake robot kinematic estimation under slippage. Pose transition was also learned after repeated trials as to how the snake robot's body gets into a posture destabilizes and then gets into the final required posture. Then relaxed to normal shape and this is repeated till the IMU values report a full 360 degrees turn completing one revolution. This mixed piece wise gaits are sufficient to scan the surrounding in full and thus we can accurately track where the target sound source is and thus solve the forward back problem and SSL using minimum mics as possible. A demo of this work in video is giving in the link [74].

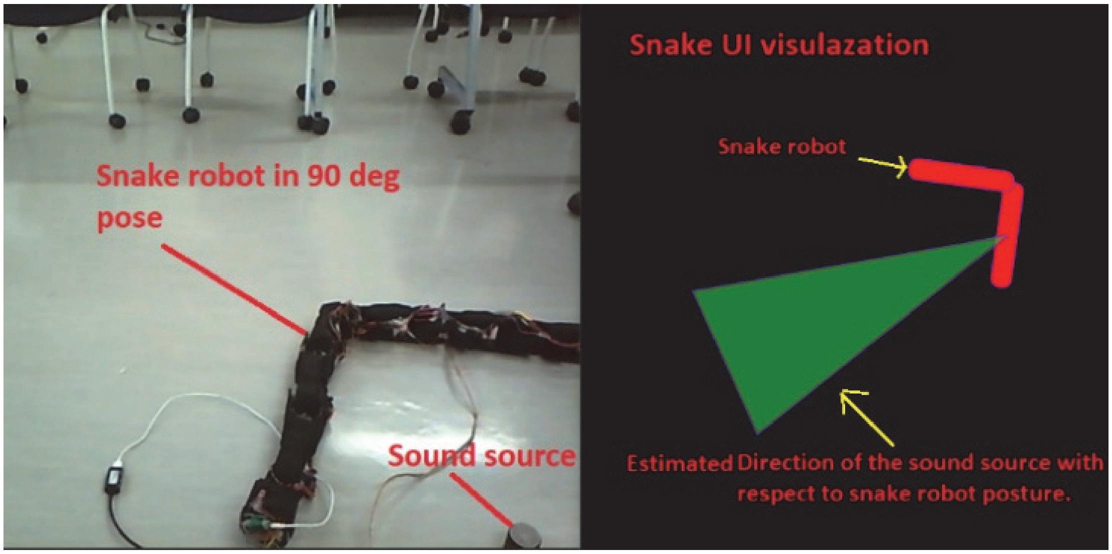


Figure 11: Figure of actual Snake robot in L shape pose with sound source., the user interface showing the direction of the source calculated/estimated with respect to the snake robot.

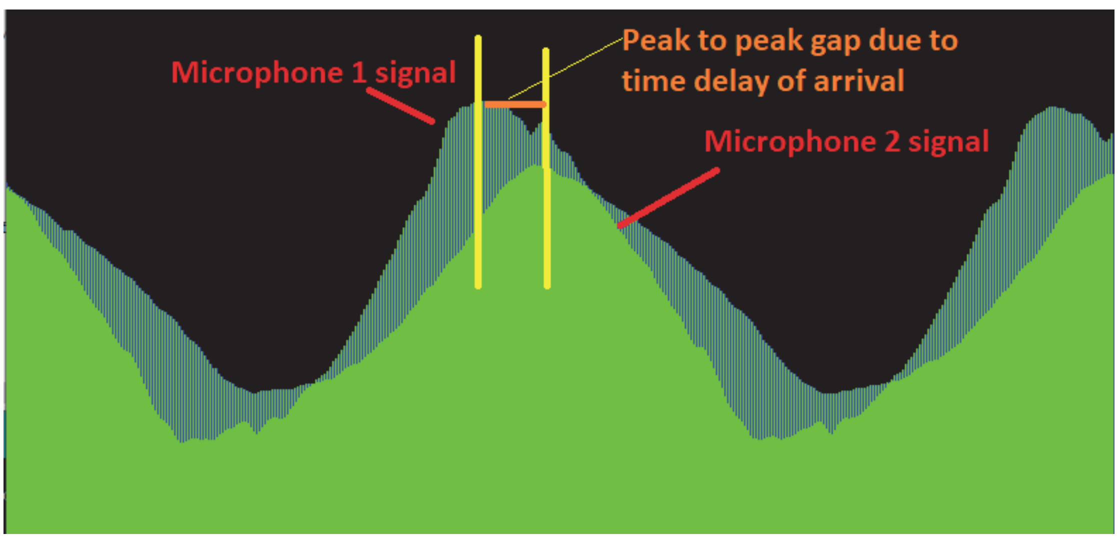
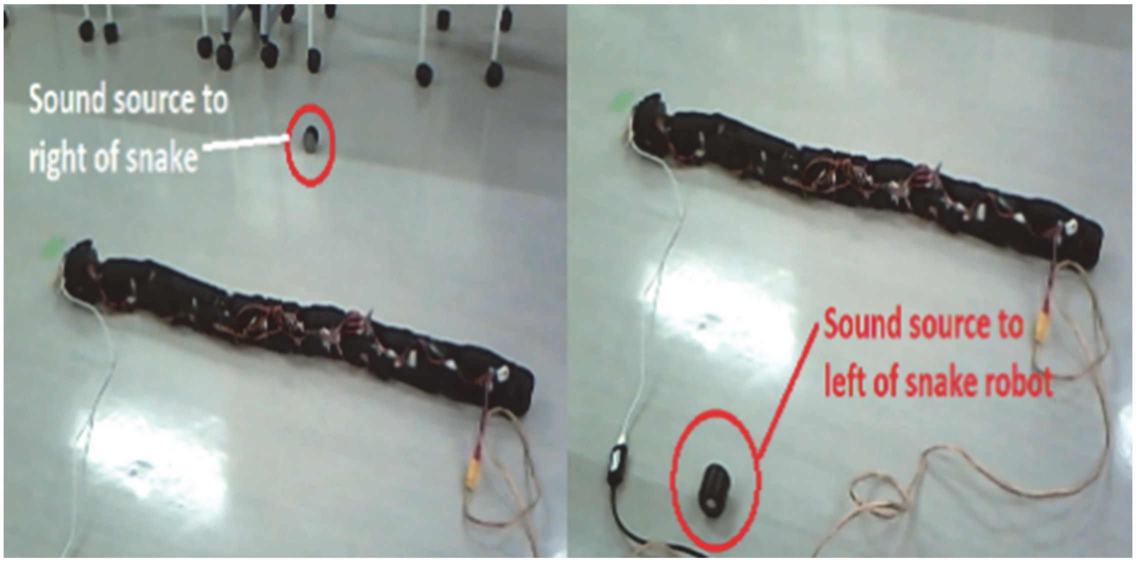


Figure 12: Peek to peak graphs showing a shift from data received in Mic1 and Mic2 as a result of time delay of arrival.



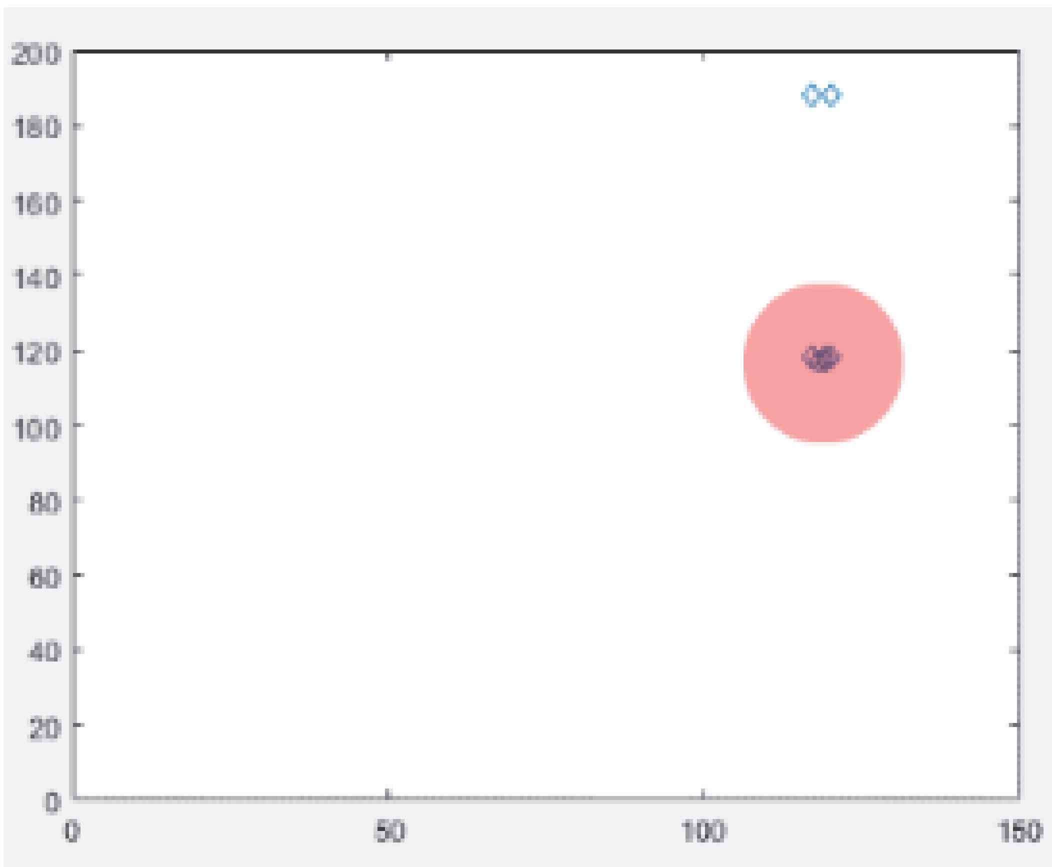


Figure 13: Snake robot not in L shape, speaker to left and right of the snake robot. Localization graph for both left and right shown

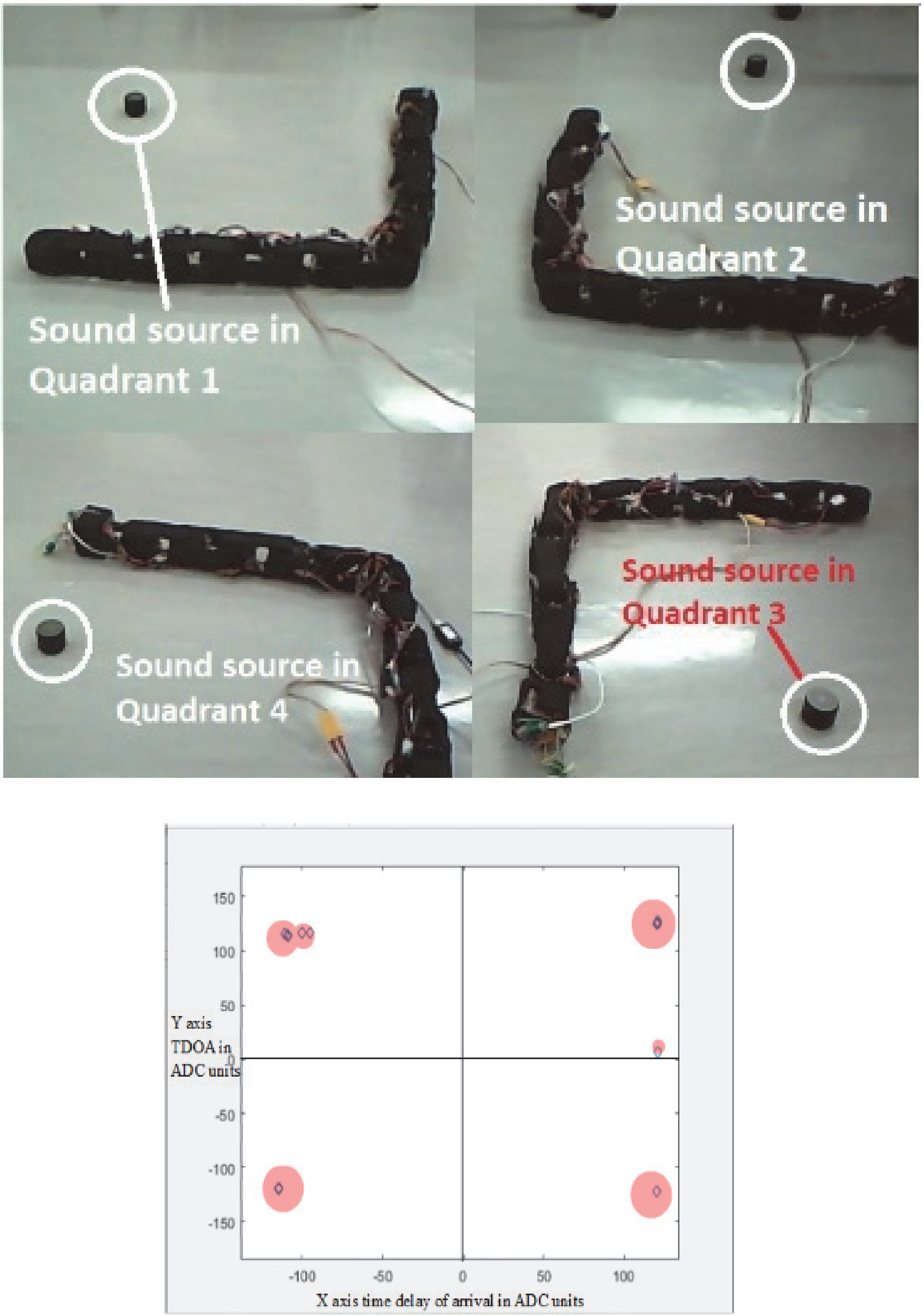


Figure 14: Shows the non-ambiguous of sound source detection in 4 quadrants, with only 1 false positive among 25 readings. The radius of circle indicates the density of similar reading.

The sound source when placed in left or right of snake when the snake robot uses only 2-3 mics (Fig 13) and is straight, gives an ambiguous solution but when the snake robot takes an L shape and localizes with one pair of mics along X axis L leg and Y axis L leg (Fig 14) gives a unique solution and thus solving the ambiguity in solution. This is the proof that using minimum mics but by posture reconfiguration we can get better results in SSL.

5.4 Conclusions and Future Work

We showed that by using just a minimum of 3 mics and using pose reconfiguration in multiple degrees of freedom of the snake robot we could localize with reasonable accuracy of +/- 5 degrees. We also showed interesting sound tracking behaviour mimicking the biological snake. In the next iteration we plan to use a differential gait to localize more naturally with differential gaits. But this later attempt would need more microphones and a better robust snake robot hardware with networked motors and higher torque. We will also expand our work on track and move feature in the next paper The main objective of this paper was to show that using posture reconfiguration which is natural to multi DOF robots we can do 3D sound source localization using a minimum number of mics. Other works used pinnae and an array of mics which were more than 3 in number to localize. Thus, our system is more resource minimal, resource effective and is a novel way of sound source localization using multiple DOFs. We also solved the classic forward backward problem found in sound source localization system through our snake robot solution approach.

5.5 Limitations

The platform for the snake robot should more accurately be manufactured to overcome errors in positioning due to backlash in the servo output shaft and connecting modules.

More novel and minimal gai maneuvers involving only the first 3 modules of the first half of the body should be designed so that localization in tight spacing can happen. Right now for doing 360 degree localization the entire Snake robot body has to maneuver a full circle. We showed 3D localization and tracking with head and neck, it is possible to add a 360-rotating head in localize in 3D with limited gait maneuvering especially akin to tight space in search and rescue scenarios.

5.6 Next chapter

In the next chapter we deal with how the output of the search and rescue robots which are the survivors are treated with robotically trained surgeons to treat them. It is of good value to use robotic arms for surgery and surgeons who gained training especially on robot surgical arms to treat patients/survivors.

5.LE-SUR and Leapulator

In this chapter we present a software simulation system called LEap SURgical simulator (LESUR) (Fig 1), which incorporates a human computer interface device, Leap, developed by Ultraleap Inc., to give users training in using their hands and fingers in a dexterous way, especially for surgeon trainees. There are two interaction systems in the simulator. One is for coarser dexterity training using a Kuka style robotic arm (Leapulator) (Fig 2), and the other is a low-cost method for surgical training that can be used with a Da Vinci-like robotic surgical system. Existing surgical simulators, like the 3D systems' [173] Touch and Phantom devices, do not give enough dexterity training for finger motion. In particular, for laparoscopic and minimally invasive surgical systems, it is necessary to acquire skills with fine finger motion and dexterity. Our simulation system aims at developing superior expertise for trainees. We use a Leap motion device to capture the finger motion and a two-mode simulator to provide different levels of dexterity training. The interaction of both the simulations is through Leap motion control device which tracks the human palm without any physical contact with the device. Leap motion device is a Kinect like camera designed to capture the motion of the fingers. The surgical simulator has been designed to help train for laproscopic and minimally invasive surgeries using robots. The virtual robots have been designed to capture the hand motion through leap device and then convert the motion appropriately for the required degree of freedom.

5.1 Introduction

All style There are many commercial robotic surgical simulators for example one such company produced system by Simulated Surgical Systems, provides a stand-alone surgical simulator called the RoSS™ platform [75]. This system teaches a novice surgeon the cognitive skills to operate a Da-Vinci surgical robot. RoSS™ uses virtual reality coupled with an electromechanical platform to aid surgeons in comprehensive surgical procedures. Simsurgery [76] provides a surgical simulation platform called SEP, which is a virtual reality simulator for laparoscopy. DBox is a manual training hardware that is to be used along with SEP. Using SEP one can get training in various types of surgeries, such as cholecystectomies, ectopic pregnancy procedures, ovarian cystectomies and nephrectomies. Another company, Delletec [77], provides real surgical procedure simulators. This simulator mimics various organs and surgical scenarios, such as the presence of a tumor, with softness and structural fidelity using rubber elastopolymers. Several simulations of appendectomies, breast biopsies, herniorrhaphies, laparoscopies, lap sim insertions, and skin closures are provided with it. The company Surgical Science has developed Lapsim and Endosim [78] simulators. Lapsim comes with a haptic interface in which the surgeon feels the feedback from a joystick as if holding a surgical tool while making an incision and working through it. It comes with an ever-expanding library of modules that provide basic and advanced laparoscopic training. The company 3D Systems [79], formerly known as Simbionix [80], has developed several simulators with haptic feedback and artificial muscles, especially the Angio Mentor simulator, Arthro for orthopedics, Pelvic Mentor for simulating the pelvic space, the Da-Vinci surgical simulation system, and LAP Mentor which comes with haptic feedback. These modules are continuously updated according to surgical advancements in the field. None of the surgical simulators mentioned above give dexterity training for hands, especially not for fingers, which is an important aspect in doing medical surgeries. Our simulator is designed to help bridge this gap.

5.2 Motivation and State of the Art

Robotic technology is gaining increased acceptance in surgical procedures and is offering much more dexterity and precision than the human hand in operative procedures. This requires newer interfaces and newer types of robots that include different micro-sensors to plan minimally invasive procedures. An inexpensive surgical simulator, such as our LESUR system, would help train surgeons for advanced surgical procedures. A study reported by Howe and Matsuoka [84] describes minimally invasive procedures, image-based procedures, interaction modes, limitations of robotic surgery, and particularly the robotic surgical methods for orthopedic surgery, neurosurgery and general thoracic surgery where training and simulation are important aids before doing real surgical procedures. Human surgeons are prone to tremor and fatigue, their hands might shake and tremble, whereas a robotic surgical device is stable and untiring. Our LESUR (Fig 1) simulator uses a low-pass filter to overcome the hand tremors and makes the surgical simulation more stable. There is good geometrical accuracy with robotic tools, but the dexterity of a human surgeon's hand is limited outside the natural scale. The surgeon's hand movements are sensed by our Leap motion device and the robot is controlled to move accordingly. LESUR does not currently have a haptic interface, which is crucial in training the hand with dexterity required for surgery. Sensing, control, and mechanical design have been some of the key aspects of a robotic assisted surgical tool. We believe that a Leap motion device can help in training the human hand's dexterity for surgical application. Minimally invasive surgery is done using long slender tools. Accordingly, the LESUR surgical robot has been modelled using long slender arms. However, the sense of touch is reduced in minimally invasive surgery compared to open surgery. The Leap motion controller does not provide any haptic feedback, but it is effective in allowing to move one's fingers with dexterity and to manipulate the robotic arms with a scissoring tool end. Many research labs and companies understand the importance of surgical training through simulation in order to hone a trainee's sensory motor skills. A complete realistic simulator of a surgical procedure is not possible with today's technology because the tissue-tissue interactions, tool tissue interactions, organ and tissue interactions, and the surgeon's hand interactions in open surgery present many complex problems of simulation. This paper [84] mentions that much work has been done on surgical simulation but little attention has been given to the kind of interfaces used. Simulation can be with or without a haptic interface. Westebring's [85] paper mentions some important aspects like haptic interfaces, haptic rendering, haptic recording and haptic playback. Westebring has also worked on force reflecting hardware by calculating the interaction between the tool and the tissue.

Another paper [86] describes an accurate model of the eye, a virtual environment to be used in surgical simulation. The simulation framework of the eye was based on a large formation finite element method to be used for a micro-surgical and tele-operated robot simulation. Virtual reality [81] offers advanced human computer interfaces that allow a person to travel, feel and mimic the real world. It is an indispensable tool to experience surgical conditions and so we used it in our LESUR simulator. With this surgeon can hone their skills and improve their performance during real surgeries. Preoperative planning and simulations are critical for real time success. The Leap motion control device is very much like that of Microsoft Kinect, which has often been used in robotics for indoor SLAM (Simultaneous Localization and Mapping), mapping, and gesture control. One such example is where a Kinect camera is used with the Roomba vacuum cleaner [88]. The user moves his or her hands as if mopping the floor. This motion of the user's hands is sensed by Kinect and transferred to the Roomba as if there were a virtual bar connecting the hands and the robot. In another example [82] a Kinect camera is used for recognizing gestures and controlling a Da-Vinci robot to do gesture-based surgery. This demo was done at the John Hopkins University: the task was to use hand gestures to insert a needle in a training kit through the Da-Vinci robot. Some researchers have also controlled the robot Nao [83] via the Kinect, which does skeletal tracking so that hand elbow motions are transferred to control the individual degrees of motion of a robotic arm. They main problem with this system was a latency between hand motions and the corresponding robotic arm movements, whereas we have a low latency system in LESUR. A good simulation environment and an interaction with it helps to get better familiarization with the real robot in an effortless manner. It is not possible to give every laparoscopic surgeon training on an expensive surgical system like the Da Vinci and, therefore, the LESUR system, which is cost effective in dexterity training, would be useful. We hope our system will teach novice surgeons the required motor and cognitive skills to operate minimally invasive surgical systems, such as the Da-Vinci surgical robot, or to perform a laparoscopic surgery. Robotic technology is gaining increasing acceptance in surgical procedures and is offering much more dexterity and precision than the human hand in such procedures. This also requires newer interfaces and newer kinds of robotic systems with different micro sensors to plan their minimally invasive procedures. Robotic surgery gains from the fact that the vast knowledge base that has developed over the years in industrial research can be directly applied with minimal adaptation in surgery. The vibrations of the hand pose a fundamental disadvantage in surgery. This can be overcome easily by using robotic instruments which, in turn, can fit through small incisions. The strong hand-eye coordination in human surgeons is yet to be implemented in robotic surgery.

Robotic technology is gaining increased acceptance in surgical procedures and is offering much more dexterity and precision than the human hand in operative procedures. This requires newer interfaces and newer types of robots that include different micro-sensors to plan minimally invasive procedures. An inexpensive surgical simulator, such as our LESUR system, would help train surgeons for advanced surgical procedures. A study reported by Howe and Matsuoka [84] describes minimally invasive procedures, image-based procedures, interaction modes, limitations of robotic surgery, and particularly the robotic surgical methods for orthopedic surgery, neurosurgery and general thoracic surgery where training and simulation are important aids before doing real surgical procedures. Human surgeons are prone to tremor and fatigue, their hands might shake and tremble, whereas a robotic surgical device is stable and untiring. Our LESUR simulator uses a low-pass filter to overcome the hand tremors and makes the surgical simulation more stable. There is good geometrical accuracy with robotic tools, but the dexterity of a human surgeon’s hand is limited outside the natural scale. The surgeon’s hand movements are sensed by our Leap motion device and the robot is controlled to move accordingly. LESUR does not currently have a haptic interface, which is crucial in training the hand with dexterity required for surgery. Sensing, control, and mechanical design have been some of the key aspects of a robotic assisted surgical tool. We believe that a Leap motion device can help in training the human hand’s dexterity for surgical application. Minimally invasive surgery is done using long slender tools. Accordingly, the LESUR surgical robot has been modelled using long slender arms. However, the sense of touch is reduced in minimally invasive surgery compared to open surgery. The Leap motion controller does not provide any haptic feedback, but it is effective in allowing to move one’s fingers with dexterity and to manipulate the robotic arms with a scissoring tool end. Many research labs and companies understand the importance of surgical training through simulation to hone a trainee’s sensory motor skills. A complete realistic simulator of a surgical procedure is not possible with today’s technology because the tissue-tissue interactions, tool tissue interactions, organ and tissue interactions, and the surgeon’s hand interactions in open surgery present many complex problems of simulation. This paper [84] mentions that much work has been done on surgical simulation but little attention has been given to the kind of interfaces used. Simulation can be with or without a haptic interface. Westebring’s [85] paper mentions some important aspects like haptic interfaces, haptic rendering, haptic recording, and haptic playback. Westebring has also worked on force reflecting hardware by calculating the interaction between the tool and the tissue.

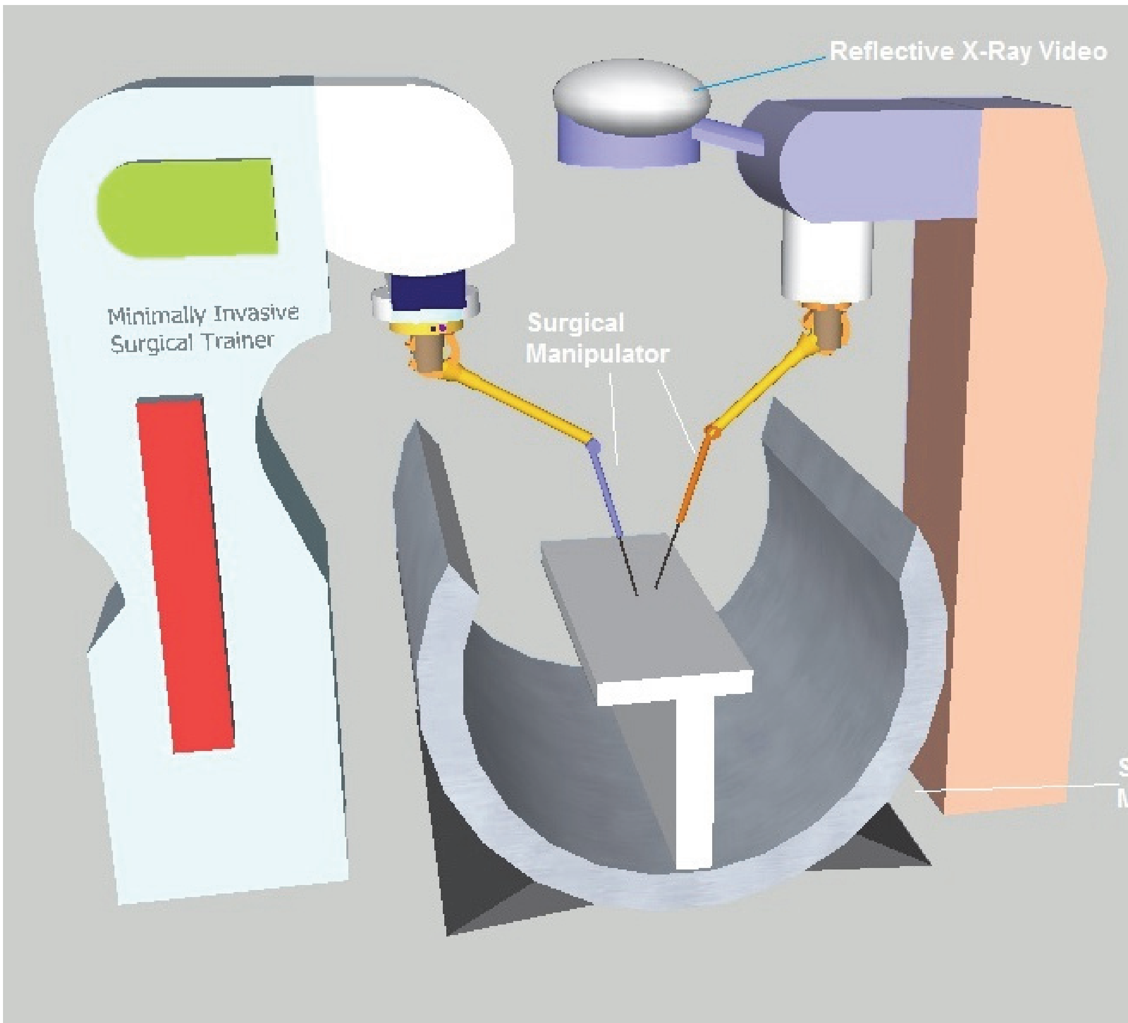


Figure 1: LE-SUR leap surgical simulator complete simulated setup.

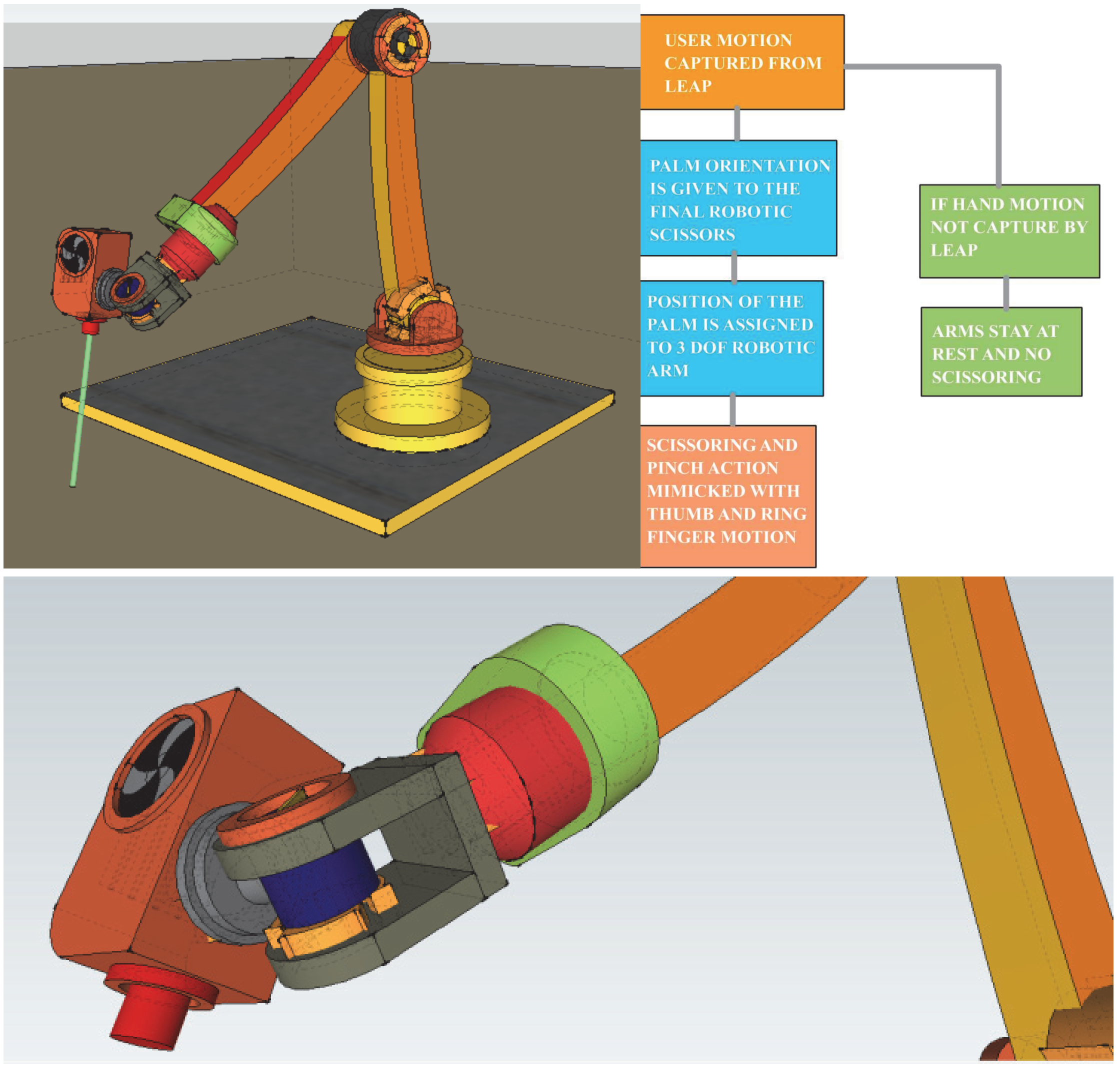


Figure2: Leapulator- Leap motion device robotic arm simulator.

Sensing and control, mechanical design have been some of the key aspects of a robotic assisted surgical tool. Here we believe that Leap motion device will help and be novel in training the human hands dexterity for surgical application. Minimally invasive surgery is done using long slender tools. In LE-SUR also the surgical robot has been modeled using long slender arms. But minimally invasive surgery has reduced the sense of touch when compared to open surgery. Using the Leap motion controller, the user will not get haptic feedback, but it has been design will the sole purpose of being able to move ones fingers with dexterity and manipulated the robotic arms with scissoring tool end so. Many research lab and companies understand the importance of surgical training through simulation as it gives the trainee to hone his sensory motor skills. A complete realistic simulator of a surgical procedure is not possible with today's technology because the tissue-tissue interactions, tool tissue interactions, organ and tissue interaction, surgeon's hand interaction in open surgery are a huge complex problem of simulation. This paper mentions that lot of work has been done on surgical simulation but little on the kind of interface used. Simulation can be with or without a haptic interface. Their paper mentions some important aspects like haptic interfaces, haptic rendering, haptic recording and haptic playback. They have also worked on force reflecting hardware by calculating the interaction between the tool and the tissue.

Another paper [86] describes about developing an accurate model of the eye, a virtual environment to be used in surgical simulation. The framework of the eye was based on large formation finite element to be used for a micro-surgical tele-operated robot simulation. The advancements in computer science and industrial science will help much more than a simple computerization of medical records. Virtual reality is acting as an advanced human computer interface which allows a person to travel, feel and mimic the real world. Haptics which is about psycho motor study and touch with virtual reality is an indispensable tool to experience surgery and surgical conditions. This will allow surgeons to hone their skills and get a high success rate during the real surgery. Preoperative planning and simulation prove critical for real time success.

The leap motion control device is very much like the Microsoft Kinect which has been excessively used in robotics for the purpose of indoor SLAM (simultaneous localization and mapping), mapping and gesture control [90][92][93][94]. One such example is where a Kinect with Roomba is used as a vacuum cleaner. The user moves his hand as if he is mopping the floor and the Kinect observes this. The motion of the user's hands is connected to Roomba as there was a virtual bar connect the hands and the robot. iRobot ava is a telepresence prototype which uses two Kinect sensors. One is for identifying gestures. In another example the Kinect camera-based gestures are using for controlling the Da-Vinci robot to do gesture-based surgery. This demo was done at the John Hopkins university and the task was to use hand motion gestures to insert a needle in a training kit through Da-Vinci robot. In another work the PR2 robot was tele operated with gestures through the Kinect cam. A delta robot was also controlled through in iar hand gestures. Another demo shows a Nao robot mimicking a user through skeletal tracking with the Kinect camera. ETH Zurich has designed a natural and intuitive interface to control and fly a quad copter with hand gestures. The Kinect does the skeletal tracking of the users, and the quadcopter is guided with the user's right hand as a virtual joystick and if the quadcopter is to be flipped the user raises his right hand. The user is protected by a safety gap area from the quadcopter. In yet another example a natural interface was developed between the quadcopter and a Kinect camera where the flight is initiated by raising the right hand and leaning forward and backward is for making the parrot drone forward and backward. Sin the game developers conference in San Francisco 2013, Nasa scientists [91] Jeff Norris and Victor Luo showed how they used the Leap motion controller to remotely operate a one-ton Athlete rover placed at the Jet Propulsion lab. Some researchers have also controlled a robotic arm via the micro-soft Kinect. The Kinect does the skeletal tracking, and the hand elbow motions are translated to control the individual degrees of motion of a robotic arm. They key thing here was the latency between the hand motion and the robotic arm's movement.

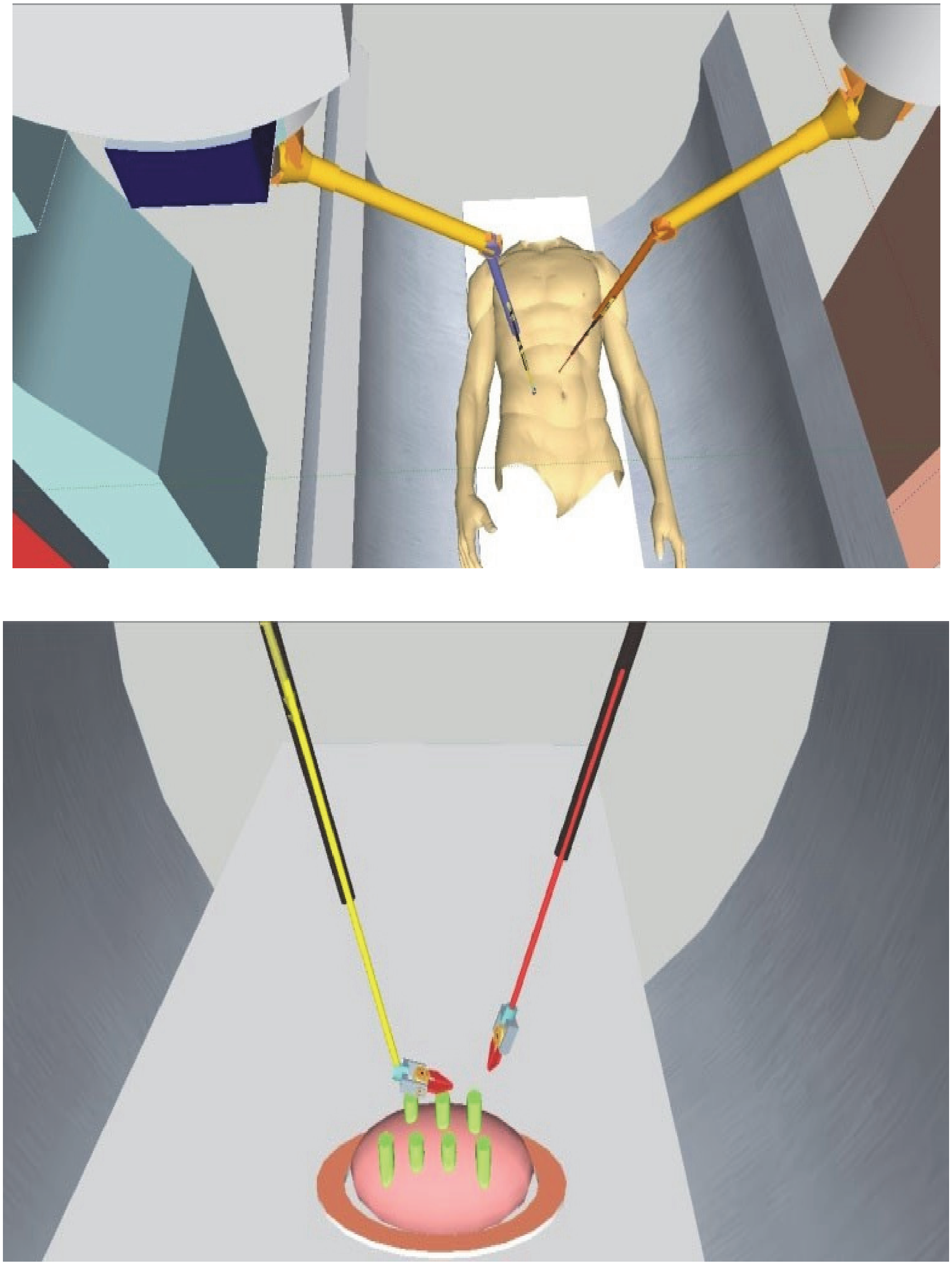


Figure 3: surgical simulation system LeSur,a target organ with tumor being operated upon (bottom)

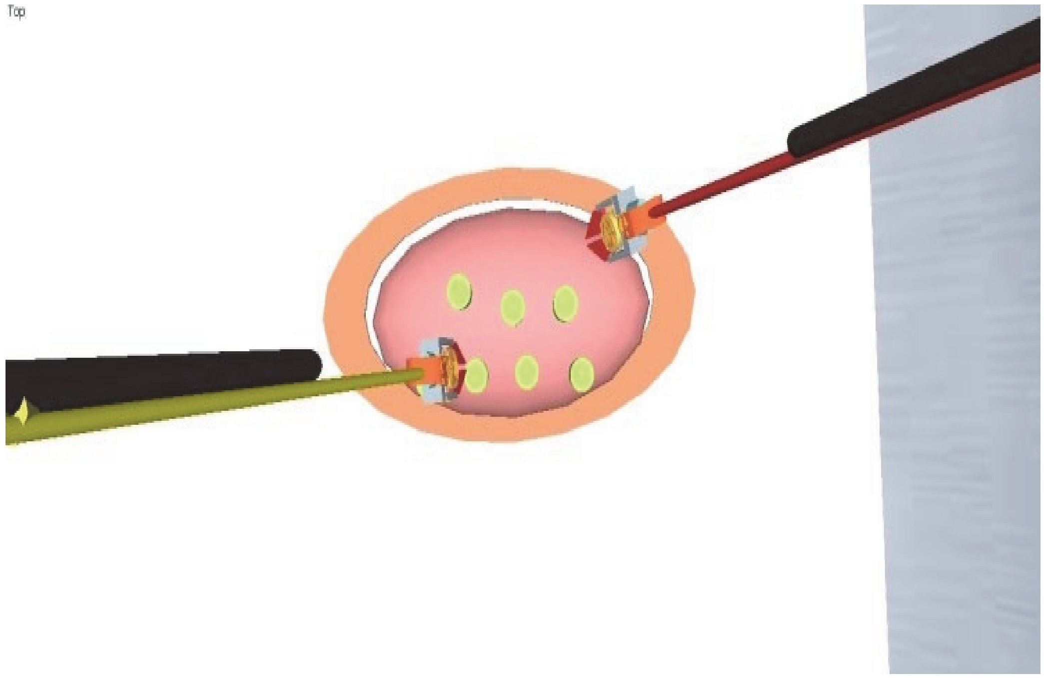


Figure 3.a: Telescopic view

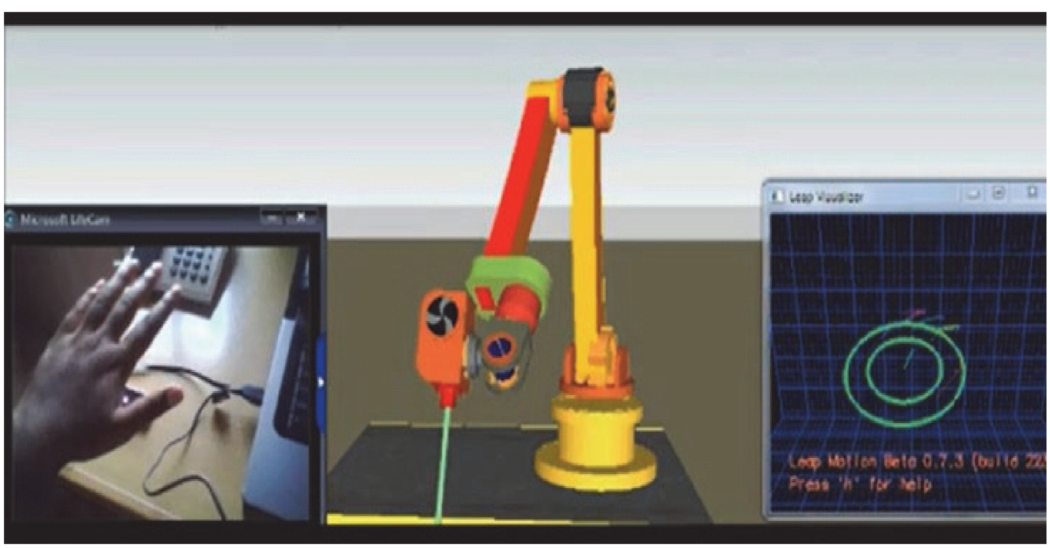


Figure 4: Coarse robotic arm training simulator Leapulator(bottom), organ operation with Lesur (top)

5.3 Description
5.3.1 Le-Sur : Leap surgical simulator

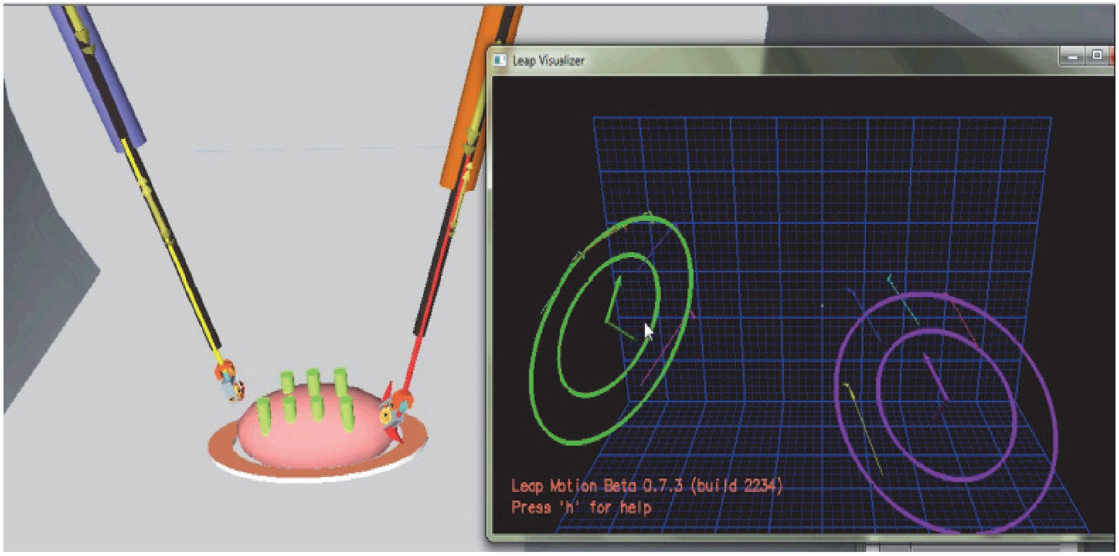


Figure 5: Le-Sur simulator operating on a text organ with two laparoscopic arms and hand tracking pose.

Le-Sur (Fig 3,4,5) is a simulator for minimally invasive laparoscopic surgical training. There have been several surgical simulators for Da-Vinci like robot but the Da-Vinci system or the trainer does not capture all the degrees of motion of a human hand. The Leap motion device is better at catching such degrees of freedom and thus becomes a natural interface to any system and especially surgical ones. For example, the scissoring is a pinch like action which is capture by the motion between the ring finger and the thumb. The simulator has been designed to give a 3D stereoscopic view onto the artificial organ that is being worked upon during the training. The demo of the simulator can be seen here [95][96]. Initially the leap motion control was given only one of the two laparoscopic robotic arms but later it was extended both. Each of the robotic arm has 7 degrees of freedom and an additional two which are dependent on each other are for the scissoring action at the end effecter. Each of the robotic arm have 5 rotary degrees of freedom and tow linear degrees. A surgical simulation should not show erratic and abrupt moves so the degree of motion of the arm was made limited and the gains were reduced. Initially the arm would not physically interaction with the organ, but later collision detection was also brought in for the interaction between the end of the arm and the artificial organ. The modleg[88][89] universal and simulator controller API is the physics engine API running in google-trimble sketchup. Both the Le-Sur and Leapulator simulators were developed in google-trimble sketchup.

Unlike a robotic tool for surgery which can be positioned very precisely a human hand cannot out of its natural size and is subject to tremor and fatigue. To overcome this problem, we have devised an audio cue which will change its tone even for the slightest displacement. This way the surgeons will get the know precisely they are position and can trail themselves for minimal tremor which will prove invaluable in laparoscopic minimally invasive surgery. The position of the hand from the Leap API is transformed to the physical model of the robot and then the motion is sent over TCP/IP to a frequency modulated audio channel in processing software. There the pitch of the sound generated is linked to the position of the arm, With the audio cue tiny to moderate vibration will result in the pitch of the sound changing. This feedback can be used by the trainee to improve his training further.

Initially control was developed for a single arm using the leap motion controller but later control for 2 hands was developed. The problem with two hands tracking using leap is that it is very noisy. A possible solution to over this is to run two leap controllers using two virtual machines using virtual box. Virtual box is used for operating system parallelization that two operating systems like windows xp and windows 7 can be run on the same computer with divided and shared hardware resources. Since the two operating systems share a different space the hand tracking of one hand can be done in operating system using virtual box and its position tracking detail can be sent over TCP/IP using a client server method. Here client server was also used to make processing software communicate with leap API running in visual studio. The frequency modulated audio cue was run in processing software. The first version of Le-sur was just developed for position training but had no physics interaction with the artificial organ but later physics interaction with the model was also incorporated.

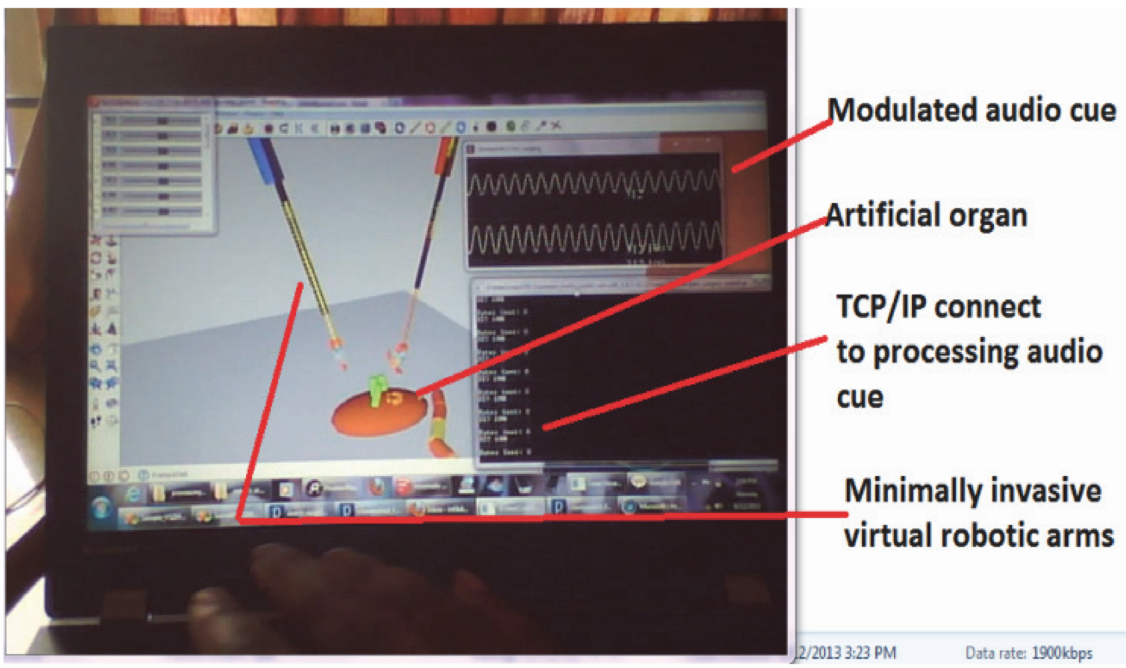


Figure 6: Leap surgical simulator with sinusoidal sound feedback.

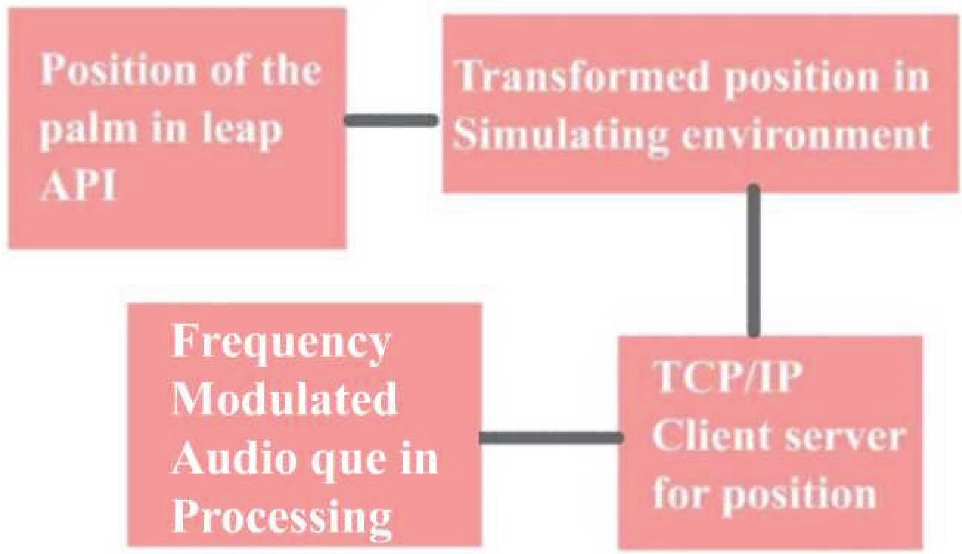


Figure 7: Software function blocks of the Le-Sur simulator.

Fig 7 shows how the frequency modulate audio que is generated by reading the position of the hand from leap motion controller API running in C++ code over inter-process communication over TCP/IP to the tone generation program in Processing software.

5.3.2 Leapulator: A virtual robotic arm controlled through leap

Leapulator (Fig 2, Fig 4) is the simulator for controlling a virtual robotic arm with leap motion controller. The manipulator used here is the virtual model of a 6 dof manipulator designed in the universal simulator and control environment. This was designed to see Leap motion can be interfaced to such hardware in an easy and intuitive manner. The robotic arm in itself has 3 d.o.f whereas the end effecter itself can rotates in its with 3 d.o.f. The motion of the palm was linked to the simulator API via the Leap motion API. The motions of the hand in 3 fundamental direction was tied to the arm's degree of freedom. The pose of the palm calculated as pitch, yaw and roll was linked with the end effectors degrees of motion.

During the initial development the motion of the palm in 3D co-ordination system from its mean position as calculated by Leap API was linked to how the robotic arm would open its degress of freedom. The linear translation freedom of the arm was converted into the rotary degrees of freedom of the arm and finally the pose of the hand was assigned to the pose of the tool head. Given that servo motor control was already developed for universal API, if a real robotic arm was constructed this gestural interface can be immediately operated with the same API. This is one advantage of using our universal simulator and API approach. To prevent erratic motion of the tool head the gains were reduced and smoothed out at the extremum. If such an interface is to be used for say a laser cutting robotic arm it is crucial that abrupt motion is prevented and the guidance of the arm happens in a smooth and precise manner. The demo of the robotic arm being controlled by leap can be seen here [131].

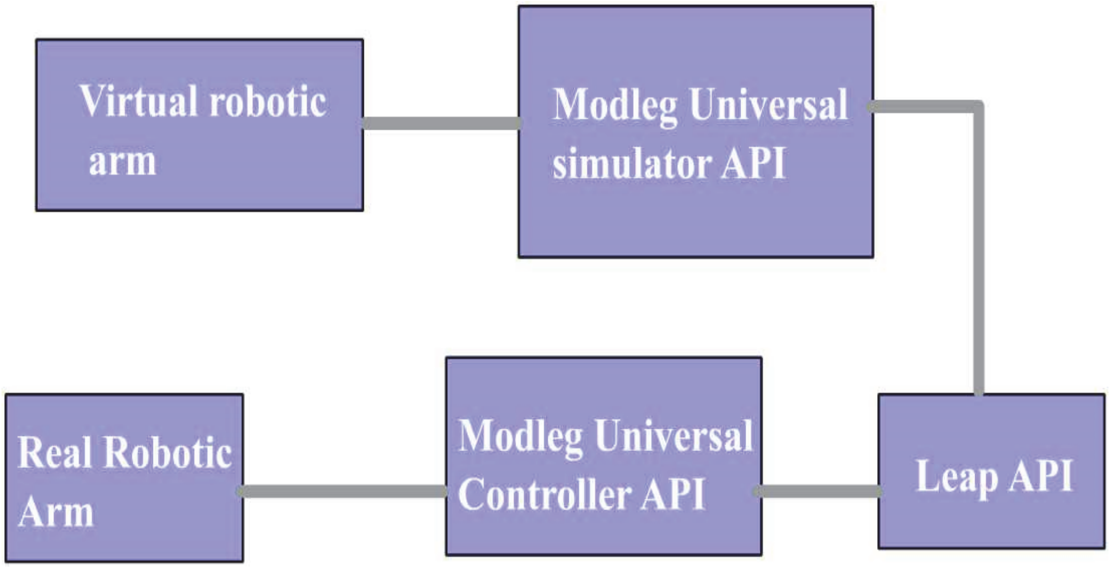


Figure 8: Leapulator functional blocks.

Fig 8 shows a previously developed Modleg API which an API for connecting virtual environment robots to real world prototypes is used in combination with leap motion controller API to control the virtual prototype of the robot.

5.4 Conclusions and Future Work

We thank the company "Ultra Leap" for their test samples which have proved invaluable for this research. In the future we would like to control a real robot arm and work on a surgical trainer organ with it. We also hope to build a prototype laparoscopic surgical robot which can be interface with Leap controller. We now in the later chapter show how this software only simulated surgical training can be extended to a real-world prototype robotic arm for surgical training with haptic feedback.

6.An anthropomorphic surgical simulator arm based on series elastic actuators with haptic feedback

We present a surgical simulator (Epsilon-1, which was designed using series elastic actuators (SEA) with off-the-shelf components. This low-cost alternative provides surgical training to surgeons by providing haptic feedback from an environment simulated by physics engines. We describe the hardware and software architecture of the surgical trainer arm in this paper. This is the first Anthropomorphic surgical arm because its dimensions and motions are of anthropomorphic nature. We present here our intuitive software simulation environment that gives multiple views for the comfort of the surgeon trainee.

6.1 Introduction

We describe a surgical simulator for surgical arm robots that can be used for many different systems with long slender arms, such as the Da-Vinci Surgical system [136]. Surgical simulation is important in pre- and post-operative planning for surgery because it helps surgeons carefully plan even the most complicated procedures and can be an invaluable tool for surgeon trainees in gaining experience before they start real-world surgeries. We used Google SketchUp (now Trimble SketchUp) and Newton Dynamics physics engine [140] for creating a virtual reality environment where a virtual model of the surgical arm, the patient's body, and internal organs are simulated.

We have chosen to use Series Elastic Actuators (SEAs) for the master robotic arm instead of using direct drive or pneumatic actuators because they allow the system to provide haptic feedback, which no other simulator currently provides. This is one of our main contributions. SEAs were introduced by Pratt and Williamson in 1995 [197], and since then have been used to provide haptic feedback in many robotics applications [130] [131] [132]. The spring used in an SEA quickly responds to any changes in the external force, which allows us to control the force by position, while generating haptic feedback. Even when an SEA is constructed with inexpensive servo modules, one can obtain a haptic device with a quick force response. Another advantage of SEAs is that they are compact and portable. For all these reasons, we have chosen to use SEAs for haptic feedback in the master arm of our surgical arm simulator system. Particularly, our design facilitates bilateral control of a manipulator for controlling soft objects like human tissue and muscles.

The contributions of this paper are as follow: the robotic surgical arm simulator is the first SEA-based with anthropomorphic dimensions, which facilitates setup around patients. That combination of anthropomorphic characteristics and of the haptic feedback is only present in our Epsilon-1 surgical simulator. It is a low-cost alternative to help surgeons gain experience in using surgical robotic arms, such as the Da Vinci, because it has been designed with off the shelf components. The viscous feedback of the insides of the body have been simulated by the physics engine, while the bones are treated like rigid and hard bodies. Moreover, our scissoring joystick design is novel, presenting three degrees of freedom of rotation, and an additional one for the scissoring action with vibratory feedback. It also has a high frequency haptic feedback that is essential for surgical arms because it helps in rendering the interactions of the surgical tool tip with the complex structure of the bones and muscles in the body more realistic.

This paper is organized as follows. In section II, we present the background and motivation for this research. Section III describes the design and implementation of our system. In Section IV, we present our conclusions and future research issues.

6.2 Background and Related research

We chose an SEA motor for making our robotic arm because it is compliant to external forces and does not have a rigid interface between the actuator and the load. An SEA system has more accurate force control, and there is less wear and tear to the motor shaft and the gear box, because its inertia is not overly reflected in the force applicator, or in the controlling environment. These characteristics are useful for making a surgical robot arm simulator that is anthropomorphic and works in close collaboration with a human. Currently available surgical arms [128] and simulators [119] have stiff actuator-to-load ratios, with a few offering torque control through current manipulation with belt driven actuation and feedback systems, akin to the Phantom Omni surgical simulator from 3D systems [119]. Compared with Phantom Omni-like surgical arm, our design uses low-cost servo modules to produce a similar force-feedback effect with a higher degree of freedom. Our system has a fast force-feedback response, because it is based on the elasticity of springs used at the output shafts of the servo motors of the arm. Our system provides a low-cost solution, because instead of using current manipulation to achieve force control like the Touch haptic device (Phantom Omni) [138], cheap off the shelf components like hobby servos motors, encoders and springs were used to provide real-time feedback to users from interacting with the simulated arm.

Currently, surgical robot arm systems do not possess advanced enough computer vision and AI technologies to perform surgeries without a human operator, just like the Da Vinci Surgical System. As an application to this concept, we developed the haptic surgical simulator-manipulator Epsilon-1 that works in close cooperation with a human user. There is one exception [136] but it is not an anthropomorphic robotic arm. Surgical simulators are useful because access to cadavers for surgical training could be a problem. So, a VR-based system like Wang[98], Huami[133] and C.V. Edmond[99] is useful. Such systems do not provide haptic feedback, while the Epsilon -1 system does this, and offers readiness to surgical personnel. Gupta et al [103] discussed the kinematics of an articulated surgical arm for minimally invasive laparoscopic surgery. We used the spring decompression on the output shaft of the servo motor to give elastic force feedback.

Another important characteristic of SEA motors is that because they are not direct drive*n*, they have a high force fidelity. This makes them suitable for anthropomorphic design because of their compliance characteristics [113], which is important for designing a robot that works closely with humans. For an anthropomorphic design, link lengths in the arm, motor size and their force fidelity are important. SEA motors fulfil these criteria, so we used them for haptic feedback and also as the driving actuator. Regarding the development of haptic devices, R.D. Howe [115] designed a master-remote robotic hand in 1992 for fine force manipulation and to provide tactile feedback. Later, Hui et al [114] developed haptic devices with 3-4 degrees of freedom, for which several different configurations of haptic mechanisms, *e.g.,* hayward and tetrahedron, were designed and introduced the concept of a virtual handle. More recently, E. Bafasa et al [134] designed a laparoscopic haptic device with a 4-DOF mechanism, which used a miniature SEA unit with some off-the-shelf components, but it is more like a 4-DOF joystick than a robotic arm. More recently, Yu and Lan [133] designed a miniaturized master-remote SEA-based haptic system for bilateral operations with torque sensing and control.In the design of our *Epsilon-1* system, we incorporate an SEA actuator with haptic feedback in a 7-DOF surgical trainer and simulator robotic arm. It also uses a master-remote arrangement with the master device being a physical real-world robot prototype, and the remote device being a virtual copy of the manipulator in a surgical 3D environment. Our goal was to obtain a fast response time and high-frequency force control for a dexterous control of the manipulator.

Our robot Epsilon-1 also caters to the need of single port surgery training. The idea of surgical simulators is to use virtual reality and surgical arms to give novice surgeons a feel of the actual surgery and improve their surgical techniques. During the surgery, the surgeon uses many surgical instruments and thus force feedback suitable for all the instruments is needed. Surgical simulators have the advantage that they allow trainee surgeon to acquire surgical experience prior to performing actual surgeries and allow pre-operative planning even for experienced surgeons. Because of the precision job that has to be done at the site of incision, requiring the surgical tool tip to follow a precise trajectory into the site of operation, robotic surgical arms like Zeus [129] and DaVinci have found good use in minimally invasive surgical scenarios. So, our objective while developing the Epsilon-1 surgical simulator was to provide training for this technically demanding job. The SEA surgical system defined for the laparoscopic surgery was built only for operation simulation at the site of the porthole for surgery. However, our system covers a large workspace as one would find in surgical robot such as the Da Vinci.

6.2.1 Series elastic actuators

Vallery etal[110] in their paper discusses about a passive torque control approach and active torque control has not been explored yet. We in our paper give our system description in hardware and software of an active torque control system which is haptic and has an SEA element. In this paper David et al [111] describe a SEA driven walking robot. Gill prat in this work and earlier work has used strain gauges to measure the force. J.W Sensinger et al [112]in their paper speaks about improvements of SEA. It gives what could be a good comparative choice of motors. For example, direct drive motors are having a high force fidelity, but they will becomes so bulky that they cannot be used in anthropomorphic design. Anthropomorphism is important when one has to design a robot that closely works with humans. Sabbaghi et al [113] used a rotary SEA to build a robotic leg for rehabilitation purposes. They argue that SEAs are a good choice for making robots that work in close collaboration with humans. Our system is also light weight and does not have the inertia problem commonly found in robotic arms driven by heavy servo motors.

C Lee et al. [133] developed a robotic leg using SEA. They used the spring-loaded inverted pendulum model to mimic the human leg using an articulated SEA-based robotic leg. They demonstrated that an anthropomorphic design and control methodology can be implemented using SEA motors: the torque control of the leg was implemented using the spring deflection of an SEA motor. Similarly, in our Epsilon-1 robotic surgical arm, we have shown that the spring deflection can lead to a precise torque control needed for slight variations in the haptic feedback when the tool tip interacts with the human body model in the physics engine.

P. Agarwal and A. D. Deshpande [131] pointed out that developing small-scale robotic applications is challenging due to unavailability of compact bi-direction torque actuators. Their system used Bowden-cable-based SEA motors with helical torsional springs, and a lightweight 3D-printed structure. Similarly, in our Epsilon-1 system, a 3D-printed honeycomb structure is used to reduce the weight of the arm, which is combined with a metal plate skeletal structure. We also use helical springs, but instead of a Bowden cable, an off-the-shelf position-control servo motor is used to build SEA units.

Yu and Lan (2019) presented a miniaturized rotary SEA motor that provides accurate torque and stiffness control. It uses a specially designed planar spring and allows bilateral teleoperation with force feedback. *Epsilon-1* uses a helical spring instead of a planar one, and our miniaturized SEA element enables accurate force control. Yu and Lan’s system can differentiate between objects of different hardness in a bilateral force feedback configuration, whereas our *Epsilon-1* system is able to show viscous interactions with the environment.

6.2.2 Surgical simulators

In recent years, a number of surgical simulators have been developed. For example, Mi et al. [128] designed a surgical simulator for the cardiovascular complex, which uses data sets from patients to build 3D models of the heart. Their system provides haptic feedback to the user while guiding the surgical probe wire to reduce error during the training resulting in better skill acquisition. In *Epsilon-1*, we provide haptic feedback through a force control servo motor in the surgical tool end and series elastic motors in the arm links. We also use two physics engines, namely Open dynamics [139] engine and Newton dynamics engine [140] in Sketchup modelling software to generate multiple interaction experiences for the user. Our simulator can adjust the viewpoint for task-specific comfort viewability. None of the virtual environments used in available surgical simulators use a physics simulator, but our system was designed using a physics engine environment, so tissue and bone interactions are more realistic. With a physics engine the force interactions are also more appropriate where can simulate a hard tissue like bones and soft tissues as well. The surgical tool in our virtual environment can be designed and changed to any shape, as our virtual environment also provides CAD capabilities to design any virtual form of the tool. The designed tool can be simulated to have a different physical interaction geometry in the physics engine. This is one unique feature and advantage of our simulation environment which is not provided in other simulation engines, at least not so explicitly.

6.2.3 Robotic surgical arms

Kameyama et al [158] designed a novel haptic surgical interface using a magneto-rheological fluid to simulate soft tissue interactions. Takagi et al [135] developed a surgical simulator where the instruments are mechanically mounted, so its loses a sense of reality as the tools have to be physically removed and then attached [126]. Middle and inner ear surgeries [100] are difficult because of the lack of good surgical simulators for these kinds of operations. Elahi Abdi et al [101] talks about a foot interface a foot interface they developed for a laparoscopic surgical robotic arm. Cheng et al [102] in his paper discusses that in minimally invasive surgery the minimal camera view makes it difficult for inexperience surgeons to do surgery Q. Liu et al [107] describes a novel surgical robot and its kinematics for single port access surgery technique; the developed SPASR robot uses a serial parallel mechanism in the design of its robotic arms. It also uses bendable sheath and flexible joints. Nisky et al [108] discuss in their paper about how hand movement and joint movement translates to teleoperated movement of minimally invasive surgical systems like the Da vinci robot. Kapsalyamov et al [129] designed a pneumatically driven compliant robotic surgical system for minimally invasive surgery. It has two arms with 3DOF each, which are controlled by a 1DOF pneumatic cylinder system. Daniel et al [104] developed the SASHA robotic arm provide haptic feedback for minimally invasive robotic surgery systems to get similar interaction of the surgical tool tip and operated region similar to laparoscopic setting. Raven 4 [105] is a surgical robot with 4 articulated robotic arms. The arms are arranged in a spherical configuration. Lin et al paper [106] discusses about a surgical navigation system used for drilling procedures. Piao et al [109] in their paper have described their surgical robot which has two identical robotic arms that have 9 DOFs each.

6.3 Overall Architecture

We compare our system with the state of the art along three dimensions. The first one concerns the development of SEA-based systems. The second one is related to surgical simulators themselves. The third comparison is with surgical robotic arms: this is important in the context of the present system because the goal of a surgical arm simulator is to train the trainees/surgeons on how to use a robotic surgical arm in real-world surgery. Our Epsilon-1 surgical simulator system (Fig. 4.a) aims to train primary surgeons. The 2 robotics arms in the full Epsilon-1 system are a pair which are mirror images of each other. In our system also the original design was to use a pair of robotic arms where one is handled by the primary surgeon and the other is operated by the secondary.

Our Epsilon-1 system is comprised of two parts: i) an SEA-based robotic arm, and ii) a virtual model of the robotic arm that mimics the motion of the real robotic arm and operates on a virtual model of human organs. When the tool end effector of the virtual arm interacts with an organ, the contact force is read from the virtual model and, using the Jacobian matrix, this force vector is converted to servo-joint torques for the real robotic arm. Based on these torques, the SEA actuators provide force feedback via the decompression of the spring in the SEA motor that we designed.

The master arm of our surgical simulator *Epsilon-1* has seven degrees of freedom, and uses hobby servo motors (Futaba RS405CB), which have a high torque-to-weight ratio (torque: 48.0 kgf×cm; weight: 0.067 kg). Each servo has a spring at the output shaft and a secondary output shaft is connected to the next link in the arm. This constitutes a bilateral force feedback system, which allows users to feel the force feedback from the virtual environment on the master arm. The SEA elements offer compliance and assist movement of the surgical tool in a virtual environment, while providing accurate force control. In rigid actuation systems, the tool tip position error is generally reduced, and position control has a tight bandwidth. However, in our design of the assisted force feedback system, we were able to get a good position feedback and control because the robot is not left free to rotate but is moving in close compliance with the user driving the arm. By adjusting the PID parameters in the position control of the primary motor shaft, the series elastic compression or expansion of the spring as measured from the secondary encoder gives good torque control. These characteristics make the system lightweight and allows it to precisely comply with the hand movements of surgeons.

Rotational springs were chosen for *Epsilon-1*, because when they are placed concentrically with the output shaft of the chosen low-cost servo motors, the compression or expansion of the torsional spring, and thus the force exerted on it, can be measured accurately. Instead of utilizing expensive strain gauges, we used cheap potentiometers as position encoders on the primary and secondary output shafts, which helps in controlling the position and the force under load. We tested torsional springs of low, medium, and high spring constants, and, based on the compliance experienced by the user and the force bandwidth, a spring of medium spring constant was chosen. A low spring constant was found to saturate the force and reduce the range of motion under compliance. A high spring constant was found to not give much assisted motion. We found that a motion range of 120 degrees (rather than a full 360-degrees motion range) is sufficient for a surgical arm.

We have used a proportional feedback controller to control the SEA actuator, and another proportional controller with a suitable gain factor for the simulated environment so that there is a close replication of the master arm in the simulated counterpart. A low-pass filter with a cutoff frequency of 5Hz is used to eliminate motion tremors.

The remote device in Epsilon-1 is a software model working in a physics-engine-based virtual environment, where contact information is calculated and reflected by the physical device using Jacobian estimation force-feedback techniques. The haptic interface of Epsilon-1 is designed having in mind the average width of a human torso [151]. As our simulator consists of a hardware arm coupled to its counterpart in a physics-engine and CAD based virtual environment, it can be customized. *Epsilon-1* can run on a Windows computer, not requiring high-end GPUs or any high-bandwidth data-communication equipment.

Epsilon-1 uses rigid body simulation to exhibit soft-muscle interactions through force feedback. A 3D model of the human body is integrated to the software side of *Epsilon-1,* which provides a haptic feedback based on contact and penetration depth of the tool end in the virtual model. A simulated endoscopic tool end is provided to interact with this virtual model of the human body. Two physics engines are used to generate various interaction experiences for the surgeon. Our system hardware overcomes hand fatigue as it is torque assisted and avoids translating tremors from the surgeon's hand to the robotic hand's virtual model.

The virtual model of Epsilon-1(Fig 1) is designed to have long slender arms because in minimally invasive laparoscopic surgery, surgical tools enter the patient's body through a small opening which limits its translation movement. The arm is modelled using the DH parameters shown in Table 1. These parameters are used to calculate the Jacobian estimation using the pseudo-inverse transpose method and the Jacobian matrix. For a given force-feedback vector on the tool end in the virtual world, the desired torque to be exerted by each of the joints is calculated, which is delivered by the appropriate servo motors. The joint angles are measured with absolute potentiometer encoders. We verified that this approach of generating the desired torques in the servo motors by reversing the force vector at the tool end in two opposite directions and noted that the torques reverse accordingly.

We have also verified that calculating our Jacobian Matrix in the conventional [103] way or by using the pseudo inverse has yielded the same result of reversing the torques when the force vector at the tool end was reversed. The virtual invasive robotic arm has a long slender tool with a scissoring end. The master arm also has a scissoring joystick, which provides force feedback. The design of our scissoring joystick is unique in that it can be rotated in three degrees of freedom, and in one degree while performing the scissoring action. For example, if a surgeon exerts more force than required, the scissoring tool end gives vibratory feedback to caution the surgeon. Similarly, to the Da Vinci surgical system, we have designed our virtual simulation environment, so it is rendered in HD resolution to give a stereoscopic feel. This resolution can be extended to 4K with a 4K monitor. In the current prototype, we have only a scissoring joystick, but in the virtual surgery simulation, we can model the tool end of any appropriate surgical tool, as in the Da Vinci system. The Da Vinci system can be wheeled into the operating bed and MiroSurge [104] can be attached to the operating table. Similarly, our *Epsilon-1* can be clamped or bolted down to any T-shaped platform. Both Da Vinci and MiroSurge systems have an endoscopic camera attached to the arm. In the same way, *Epsilon-1* provides a camera viewpoint feature so that one can virtually change the field or angle of view and gain a better view of the surgical site. It can show the endoscopic view, the organ and the surgical arm, or the full body and the surgical arm. This is shown in Fig.1 below.

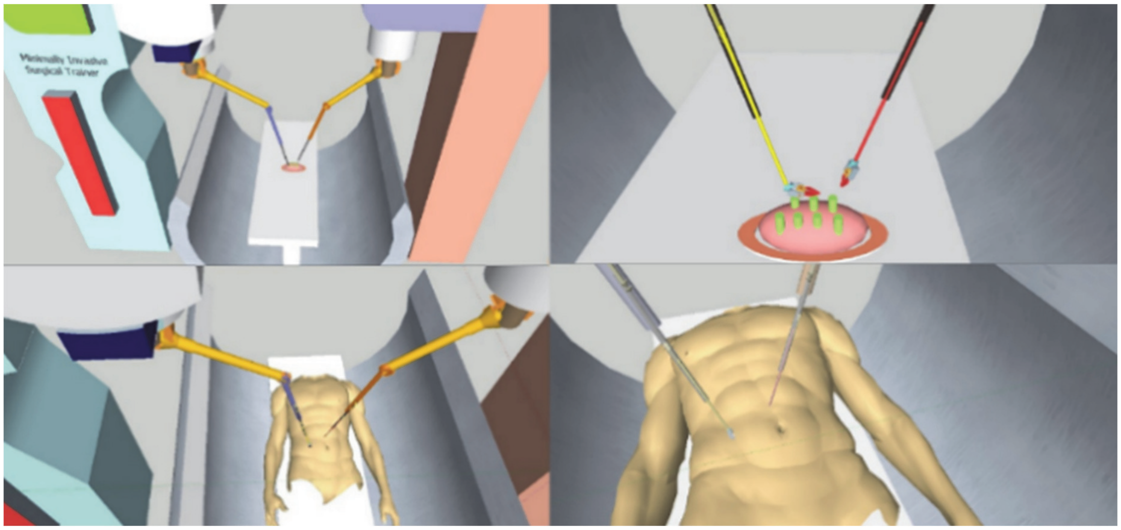


Figure. 1: Different views available to the surgeon in *Epsilon-1*

The simulated surgical environment of Our *Epsilon-1* system can be teleoperated because the interfacing with the master arm is done over RS232 and RS485 protocols. Thus, a teacher surgeon can perform a surgical simulation live for students in a classroom while being in another room.

6.4 Mechanical Design

The robot arm in Epsilon-1 (Figs. 2, 3) has seven DOF, all rotational, which provides translations in three DOF, rotations in three DOF, and scissoring action in one DOF. These seven DOF are realized via seven servo modules —four are SEA servo modules, three are micro-smart servo modules for the wrist — and there is an eighth servo for the scissoring joystick. Every one of the four SEA connect two links of the arm, and consist of a Futaba 405CB servo motor with its output shaft connected to a spring. The other end of the spring is taken as the actual output shaft, whose rotation is measured using an absolute potentiometer with no mechanical stop. The surgical tool at the end of the robotic arm can be changed to any other generic surgical tool both in the physical arm and its virtual simulated model. The frame of the robotic arm is built with aluminium parts and 3D-printed ABS plastic spacers with honeycomb mesh pattern, which makes it light weight and adds to the integrity of the structure.

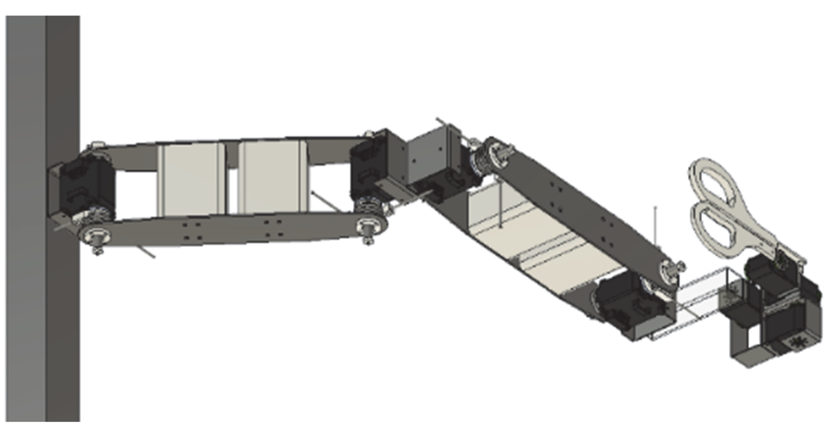


Figure. 2.a: Mechanical design of the robot with two links, one 3DOF wrist joint and scissoring end.

Figure 2.b: Showing the CAD model of the SEA motor element

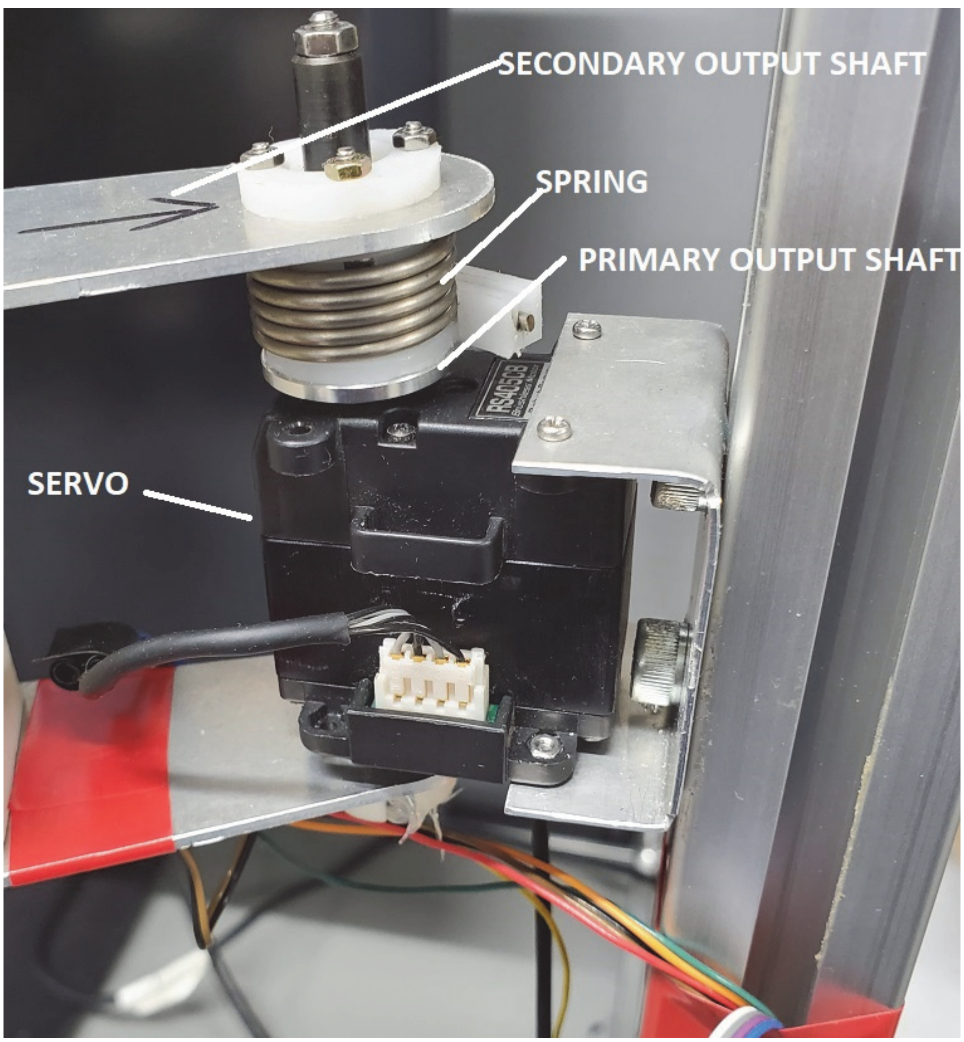


Figure 2.c: Showing the SEA motor prototype built from components off the shelf.

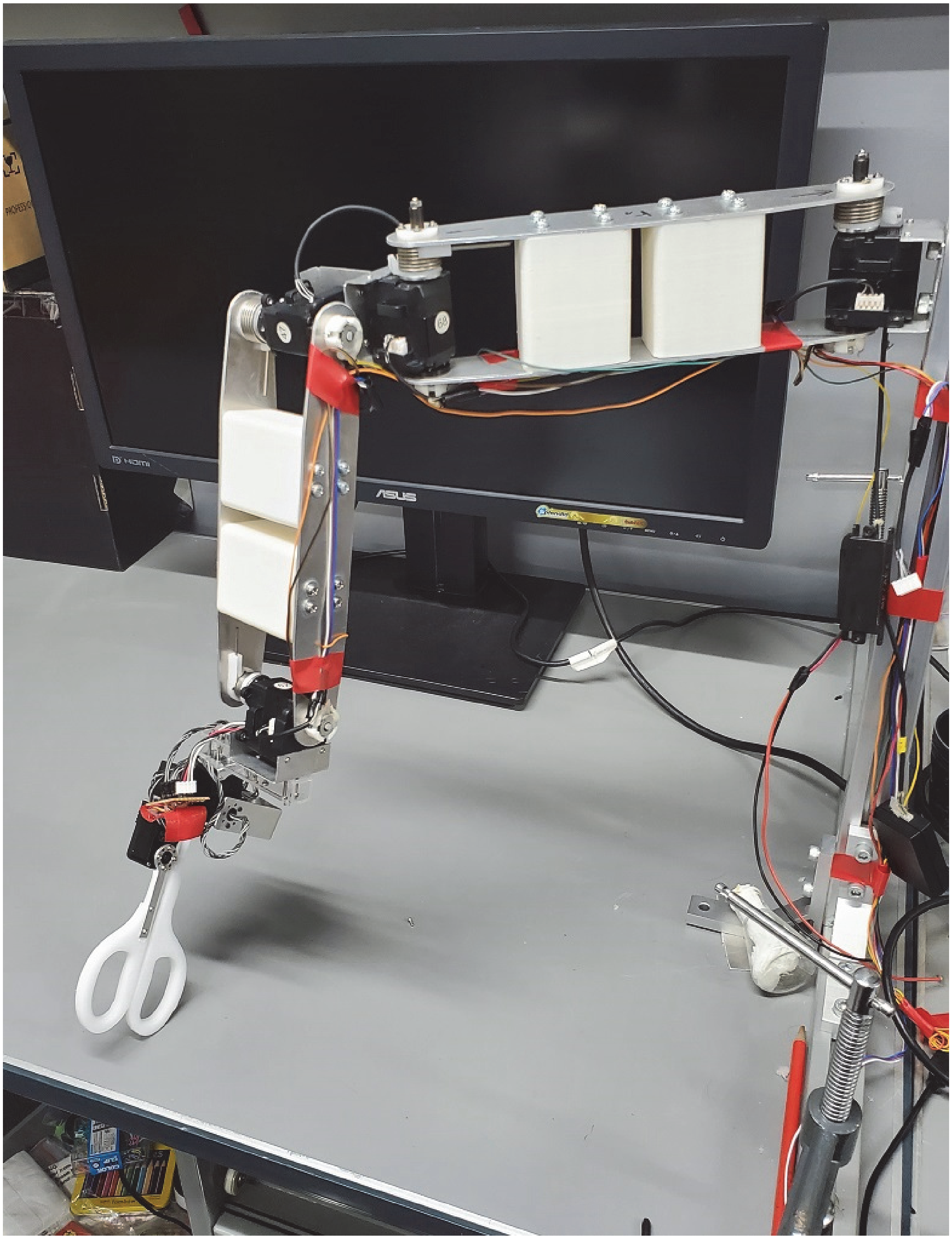


Figure. 3: A single motor Series Elastic Actuator unit and the surgical sim arm.

Our Epsilon-1 simulator provides value in the form of compliance with viscosity feedback that is obtained by the depth of penetration of the surgical tool tip in the simulated body organs.

Since we have a large workspace, we have constructed the robot in the form of an anthropomorphic arm that can cover the entire width of the body and can choose any point for the surgical port hole [103]. The series elastic actuator elements designed in other papers [130][131] are different as we use a digital smart servo network-based motors and our SEA element is different in its construction as shown in (fig3) which uses a limitless potentiometer, a rotational spring, a Futaba smart servo, being much simpler and cost effective to produce and manufacture.

6.5 Electrical design

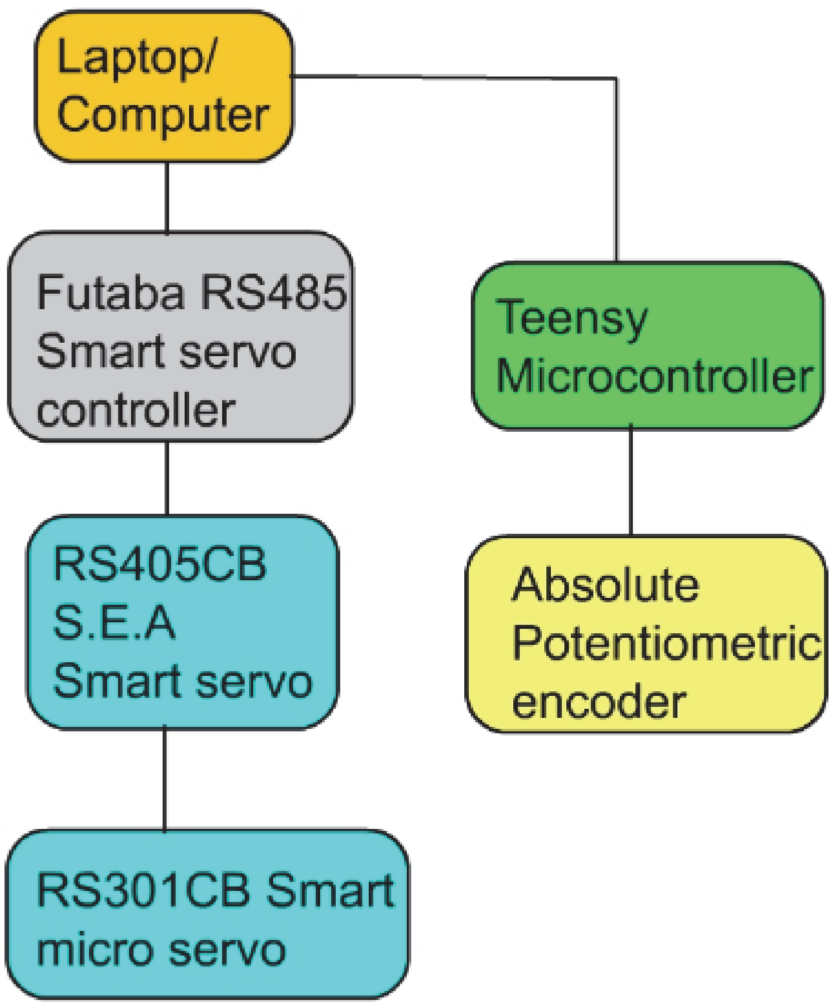


Figure. 4.a: Hardware schema and the Virtual arm in SketchUp

All servo motors and SEA modules in the arm are powered by a 12V bench power supply. The potentiometer encoders are connected to the Teensy Arduino microcontroller (Fig. 4); their positions are read on individual analog-to-digital converter ports. Potentiometer angle values of the arm joints are sent over a USB-to-serial port in real time as read by the Teensy Arduino microcontroller. The servo modules are commanded using a USB-to-RS485 smart servo controller from the laptop.

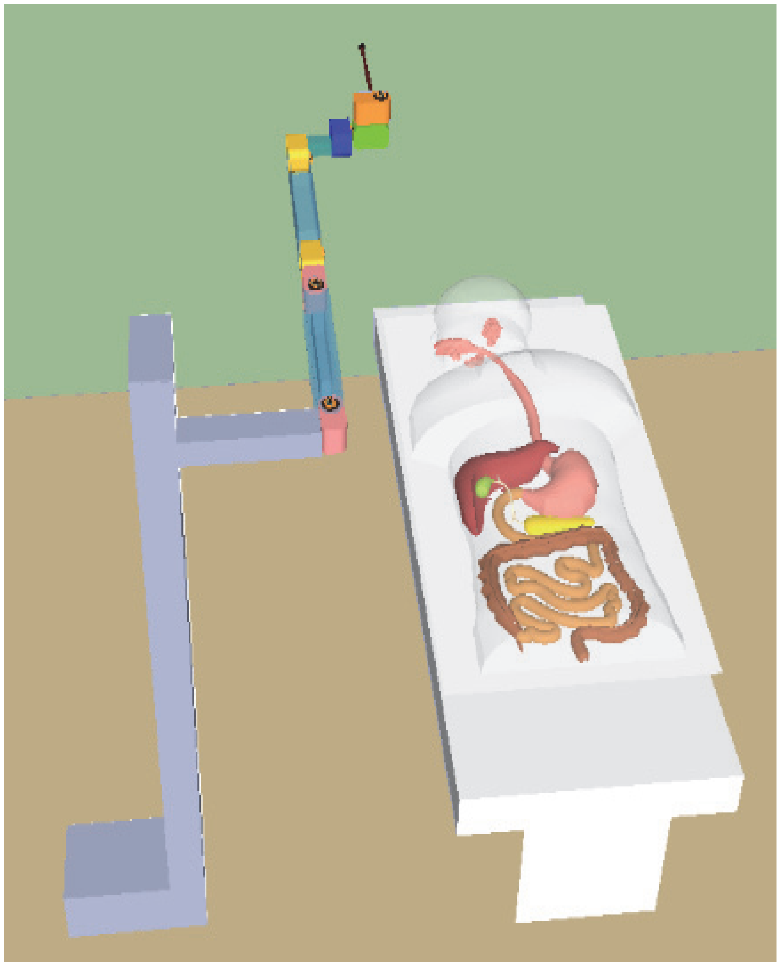


Figure 4.b Simulate environment setup

6.6 Software design

The SEA logic is executed on a laptop, which computes the difference between the present readings of the servo motor encoder and series elastic output shaft encoder and sends the output of the motor proportional controller via RS485 servo commands. Both encoders are read in parallel by an RS485 servo-controller and by a Teensy Arduino microcontroller. The configuration of the arm is read and sent to the physics engine. The virtual model of the robotic arm interacts with the virtual model of the artificial organ or the surgical site in the simulated patient's body. The contact force interactions are calculated by the physics engine (Fig. 6), which are used to compute the contact force vector and servo joint torques using classical kinematic equations with Jacobian pseudo inverse method. The spring force parameters are calculated to exert a reactionary force back in the master arm. We have used two simulation engines for the virtual environment of the surgical arm: one is the design and simulation environment of Google Sketchup with Sketchy Physics engine, and the other is the Open dynamics engine (ODE) [139]. In sketchy physics, it was not possible to obtain the collision force vector, but it is a good design environment. In ODE, the collision force vector can be calculated based on the collision force normal and collision depth parameters. The software system integrates multiple subsystems working at the same time, like the position feedback, forward servo control, and the physics engine.

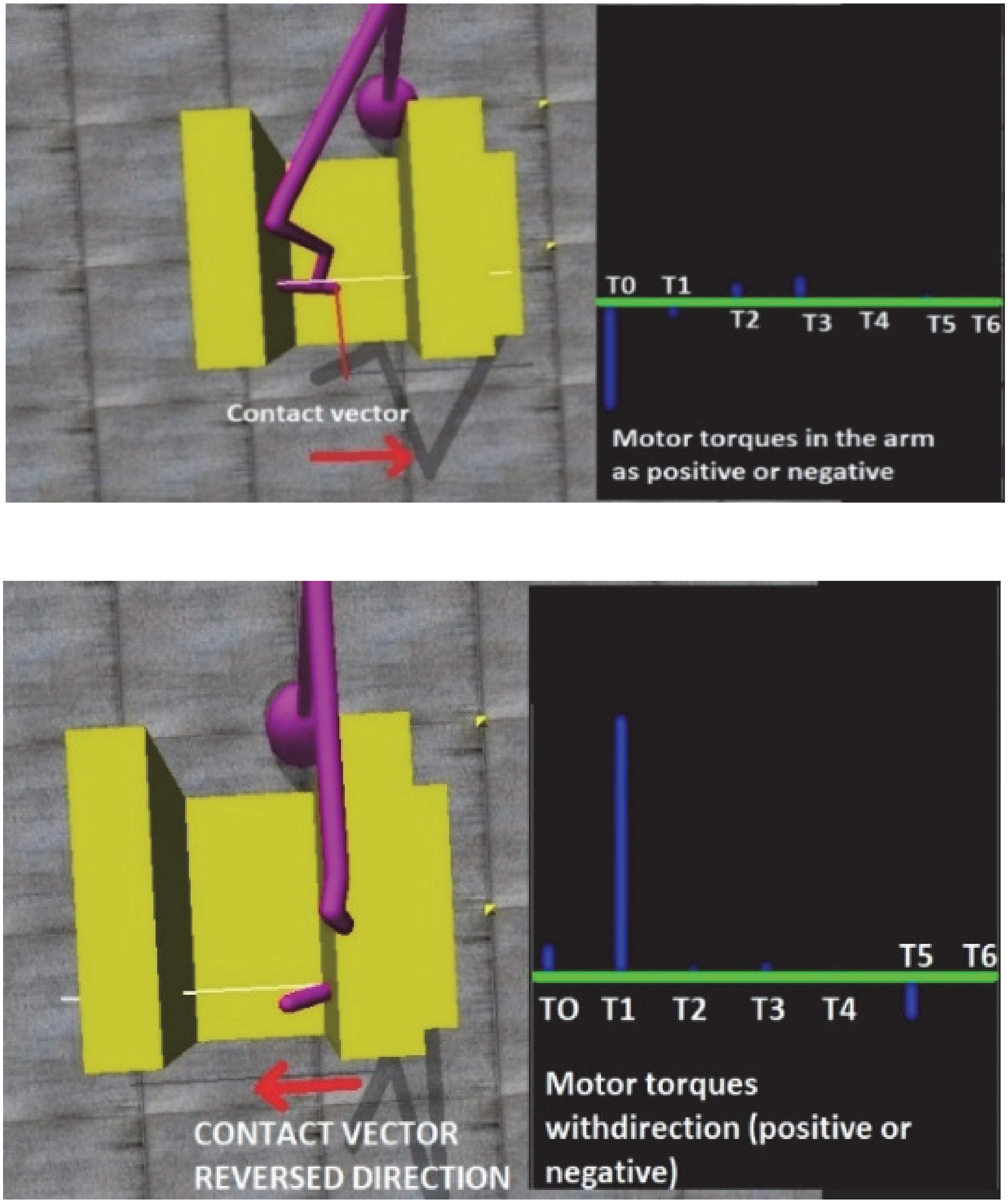


Figure 5: Joint torques corresponding to the contact force vector as calculated by Jacobian.

The joint torque changes direction as the contact force vector reverses, which is shown as a white line in Fig. 5. The clockwise and anti-clockwise motor torques are shown as positive and negative bar graphs, respectively. The yellow block is for testing with two opposite walls in the virtual environment if the torque resulting from the Jacobian changes direction with the contact force vector.

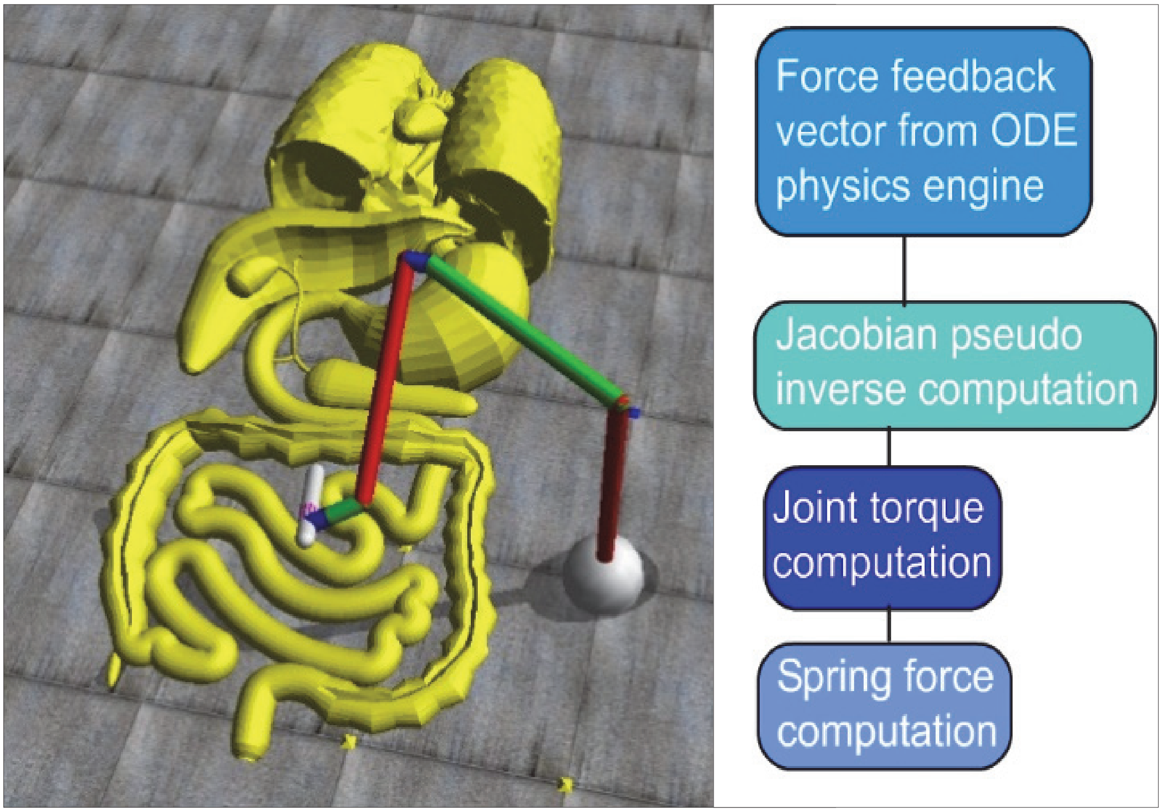


Figure 6: (Left) A virtual model of body's internal organs in Open dynamics physics engine. (Right) Computational flow of force feedback.

The joint angles of the master robotic surgical simulator arm are mimicked in the virtual arm: as one moves the real arm, the virtual arm moves accordingly. When the tip of the robot arm comes in contact with the virtual human body model, a force vector is generated, which is considered in the computation of the joint torques using the Jacobian matrix method. The Jacobian method uses the robot's DH parameters. After obtaining the joint torques (Fig. 7), the spring compression needed to exert the desired force feedback by the servo spring series elastic motor in each joint are calculated. This is how the force feedback effect is exerted by the master robotic surgical arm on the user.

The SketchUp environment runs our custom designed surgical simulator called LE-SUR [96]. This physics engine did not have an API to read the contact force vector at specific points on the tool end of the robotic arm, so we used Open Dynamics Engine to read this vector.

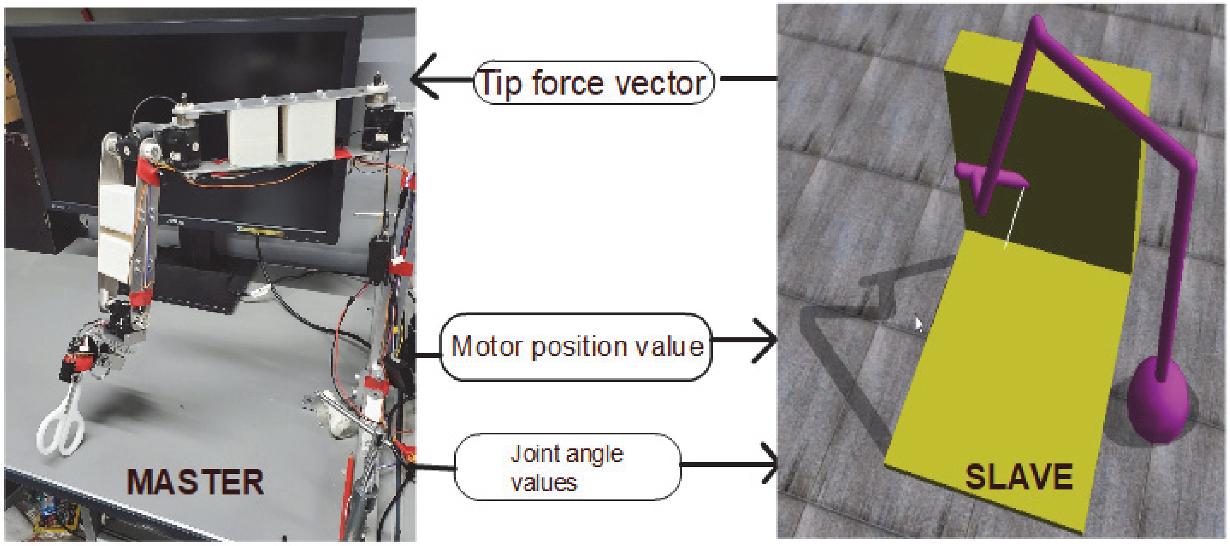


Figure 7.a: Master-remote interaction. (Right) Simulated copy of the arm (pink), object of interaction (yellow), and force vector (white). (Left) Real robotic arm prototype.

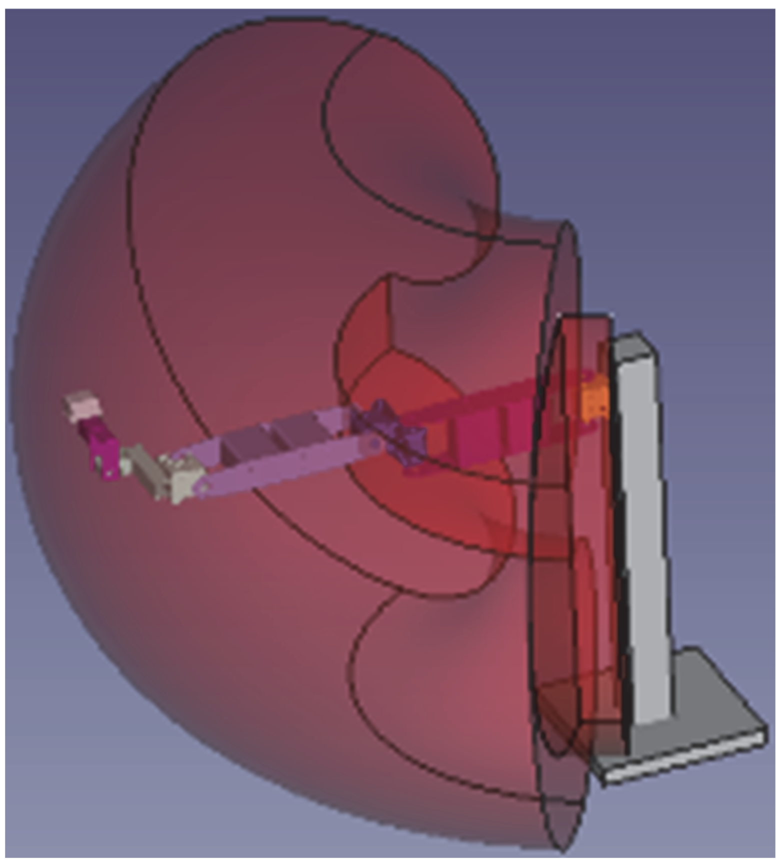


Figure 7.b: Work space diagram left, Bode plot of feedback position control (middle) and bode plot of force control right

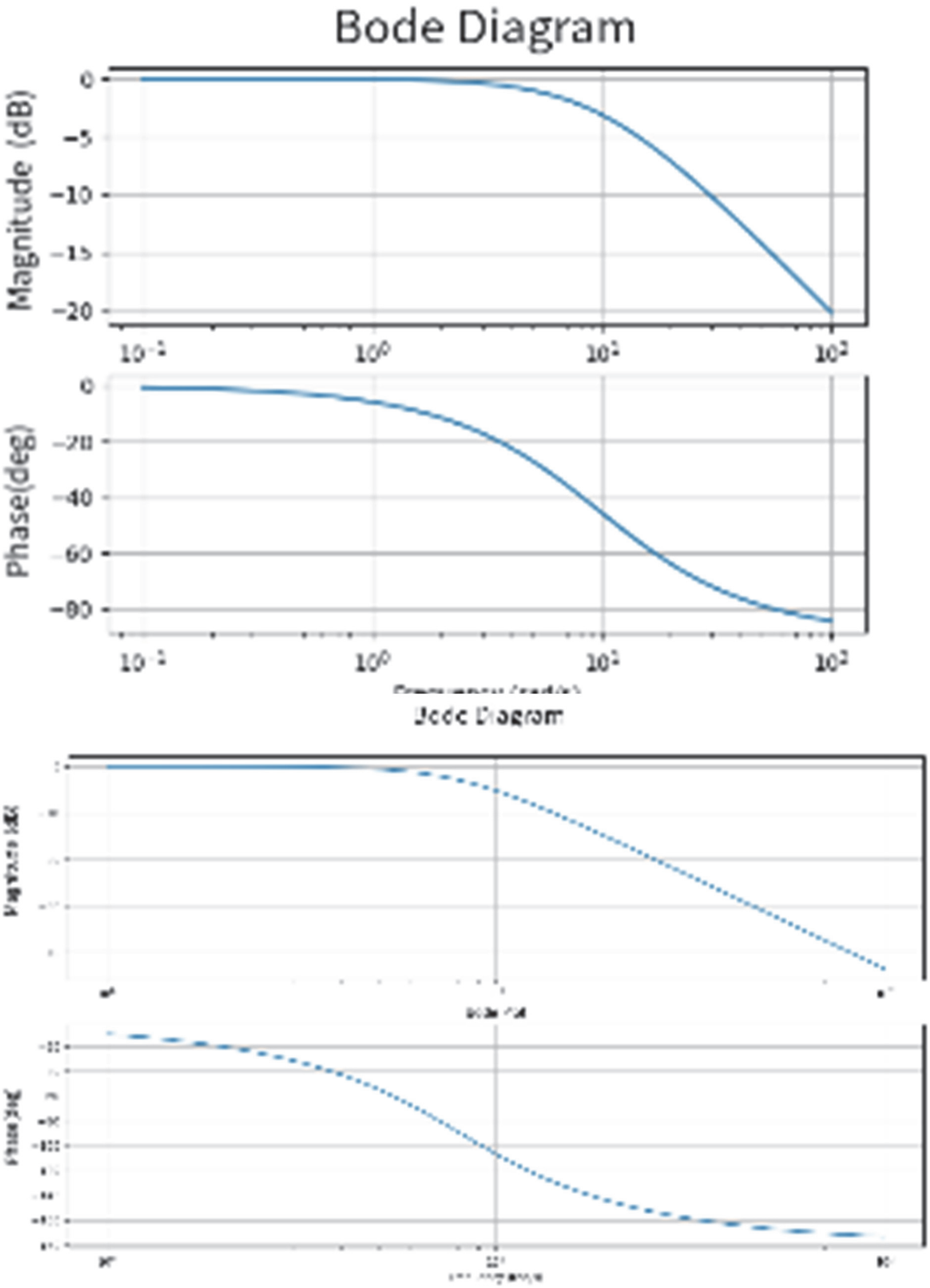


Figure 7.c : Bode plots of the SEA surgical arm

Sewell et al [126] point out the need for providing intuitive metrics as a feedback during surgical simulation that is also user specific which helps in catering to the needs of a particular trainee without the need of involvement of a surgeon. Cognitive aspects of the surgery are also important to be conveyed in the simulator and thus our Epsilon-1 surgical simulator provides Cognito-sensory mechanical feedback to the surgeon trainee. For example, one metric that has been described by Sewell et al is in the case of Mastoidectomy where the surgeon performs a saucerising procedure to gain visibility. However, for the purpose of providing additional visibility, we have developed our virtual environment with the capability to provide X-ray vision of the simulated body and a wireframe edge mode (Fig 10), which allows for better visibility during surgical training. This is a unique feature in our surgical simulator. The wire frame and X-ray mode can be replaced with CAT scan or X-ray (Fig. 8) machine views during the real-time surgery. This is one important visual metric lacking in surgical simulators these days and we provide this as one of the solutions in our surgical simulator. Another visual metric is exposure for example in their paper Sewell et al have defined that in Mastoidectomy they would drill into a bone for certain length and prevent further drilling to avoid a facial nerve. We can set the alpha transparency (Fig. 9) in our surgical model to help users gauge the depth of the surgical tool being inserted into soft tissue or bone.

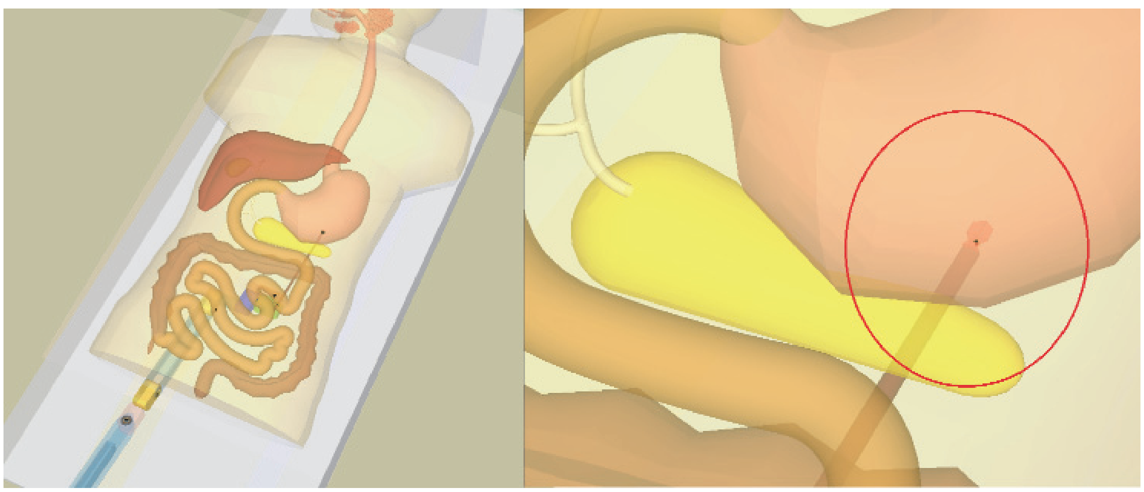


Figure 8: X-ray views, where the surgical tool tip is visible. In the alpha view, the surgical tool is not visible inside the organ. The alpha view is for bone-like structures, and the X-ray view is for soft tissue-like structures.

Figure 9: An example of alpha transparency

The wire frame (Fig 10) view is useful for knowing boundaries of organs when interacting with them in the virtual environment. The size of an organ is not always clear in the human body because other tissues and organs may cover it; this wireframe view will help surgeons to train how to precisely position the surgical knife blade and make incisions. Some of our unique features of simulator are giving cognitive visual cues [126] Xray view, alpha view, edge view. Currently there are no simulator tools to offer this level of surgical training.

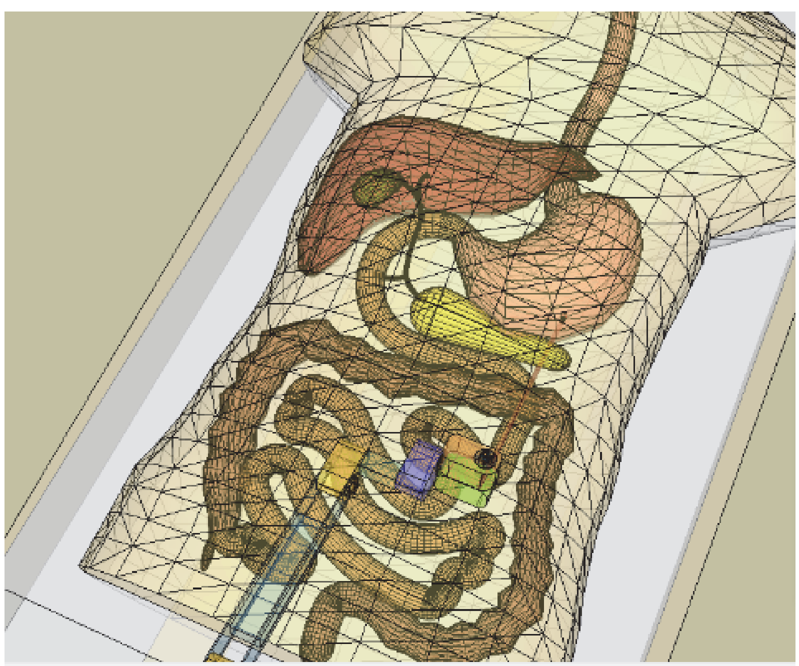


Figure 10: A wireframe edge view.

With a less complicated hardware, it is very straightforward and cheap to include a second mirrored arm in the current system, making our proposed solution cost-effective. Our system also overcomes hand tremors by using a low-pass filter, so that the tool tip does not deviate much from the intended trajectory on the 3D virtual model. This gives Epsilon-1 a competitive edge over other systems, while allowing it to be deployed with a real robotic arm doing the surgery instead of a virtual environment. Our virtual tool tip model can be changed to drilling tip. Until now none of the virtual environments used in surgical simulators use a physics simulator but our system is designed using a physics engine environment. The surgical tool end in our virtual environment can be designed and changed to any shape of surgical tool (Fig 11) as our virtual environment provides CAD capabilities to design any virtual form of the tool. The designed tool can be simulated to have a different physical interaction geometry in the physics engine. This is one unique feature and advantage of our simulation environment which is not provided by other simulation environments.

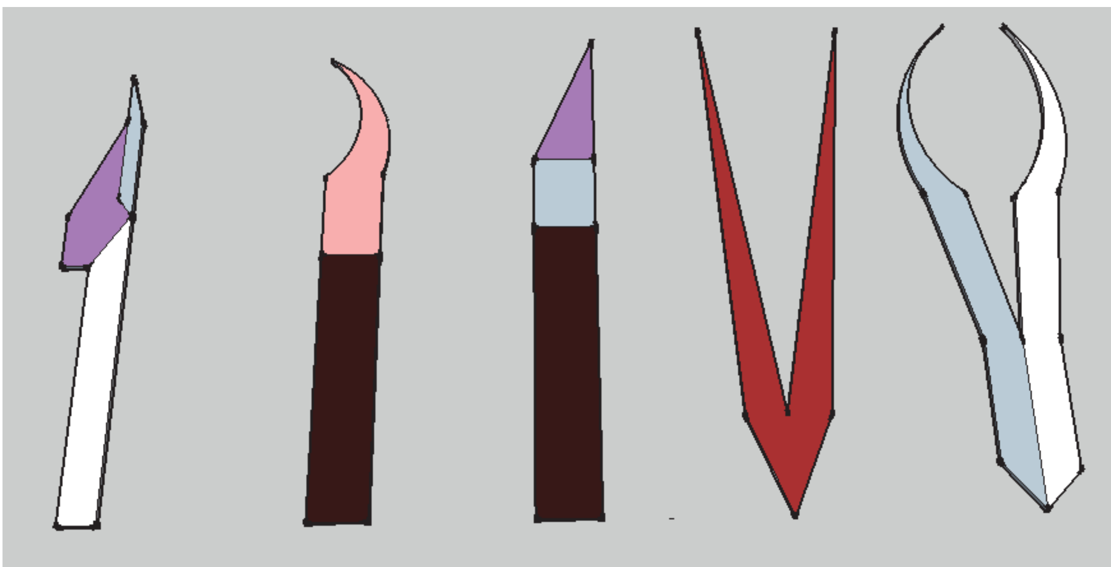


Figure 11: Multiple 3D models of surgical tools that can be chosen in our surgical simulator environment

The Epsilon -1 simulator provides motor vibrational cues to alarm users about a particular operation error or situation that needs attention. For example, if a user tries to cut a blood vessel or an organ that is not being operated upon, or exerts more force than required, then, using the inverse kinematic metrics, the motor in the scissoring degree of freedom vibrates to alert the trainee surgeon. In severe alert situations, movements towards critical areas are blocked by a harsh force feedback in the master arm.

6.7 Force feedback calculations

Though in Epsilon-1 we have used a conventional kinematic method (Jacobian Estimation) to convert the force of end effector to the joint torques, the novelty is in how we provide force feedback in our uniquely designed series elastic actuator based surgical arm. Our kinematic and force analysis is based on the Jacobian estimation method, which is needed when considering an anthropomorphic design. Our robotic surgical trainer differs in terms of hardware, software simulation used and analysis. The pseudo code for our force feedback system using SEAs is shown below.

7 *Compute θ (encoder joint angle) by the encoder.*

8 *Calculate J† (θ) using D-H* parameters. z_0 *is the angle vector and* P_0 *is the base-to-joint vector*

$$J = \begin{bmatrix} z_0 \times P_0 & Z_0 \\ \vdots & \vdots \\ Z_6 \times P_6 & Z_6 \end{bmatrix}$$

9 *Compute force vector F from simulation*

10 *Torque = J† x F*

$$\tau = J^{\dagger} F$$

11 *Calculate Δα*

12 *Torque by spring = spring constant x Δα*

$$\tau = K_p \Delta\alpha$$

13 *J† = (J† x J)-1 x J*

$$J^{\dagger} = \left(J^{\dagger} J\right)^{-1} J$$

Where θ is the angle measured at the secondary output shaft using the encoder. From the D-H parameters, we compute the Jacobian transpose. We calculate the force feedback vector from the virtual environment. Then, using the Jacobian method and this virtual force vector, the joint torques in each of the 7DOF are calculated. Δα is the difference between the primary output shaft angle and the secondary output shaft angle, which shows how much force the series spring in each of the joint should be deformed to exert the computed joint torques from the Jacobian estimation method.

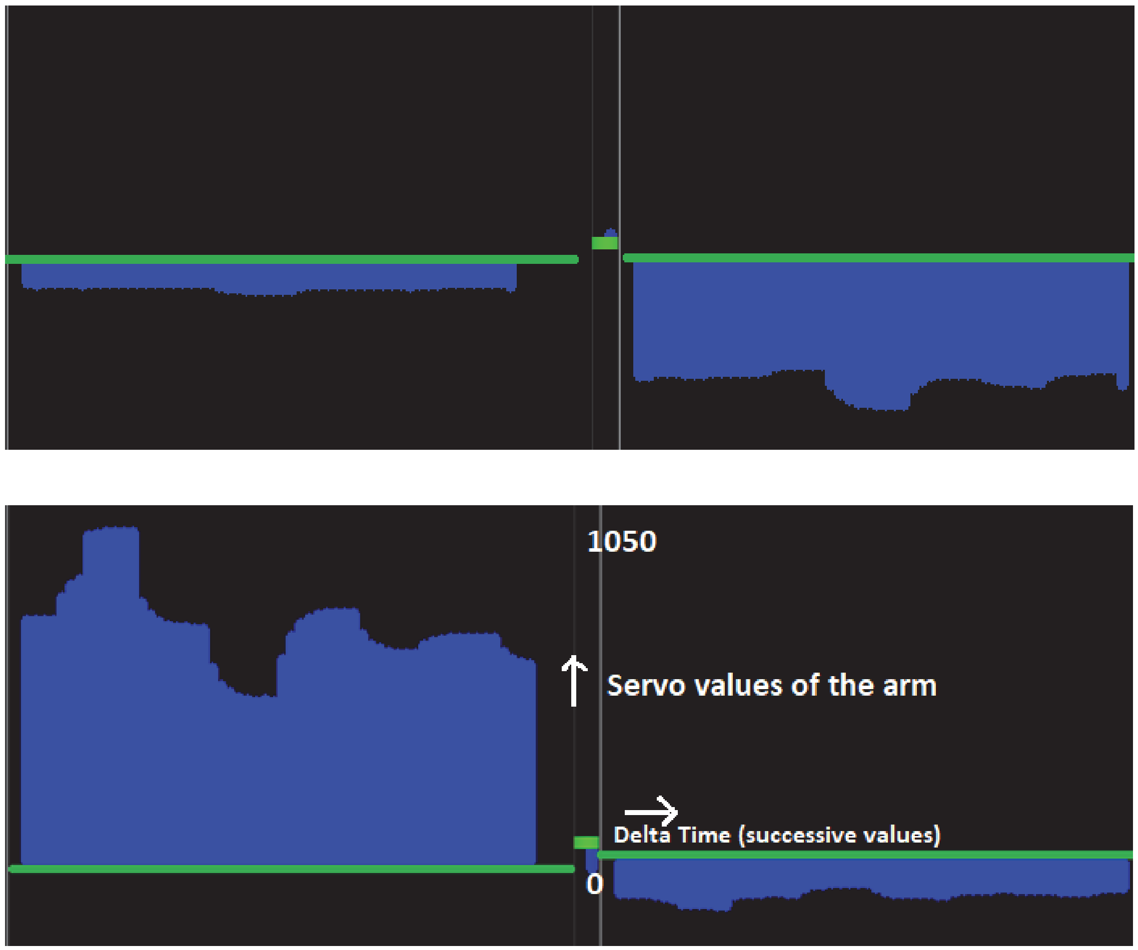


Figure 12: Time series graphs of the joint forces as indicated by servo decompression position values.

Fig. 12 shows the time series plots of the major link of the surgical arm. From these, we can see that when the contact force vector reverses, the joint angles are also reversed. This results in the force-feedback effect in the arm. Now, based on the calculated torques, the an SEA actuator provides force feedback based on the decompression of its spring. This requires specifically manufactured gear boxes with expensive current-controlled drivers We use Denavit-Hartenberg (Table 1) parameters to describe our robot.

TABLE I. D-H PARAMETERS

S.No	**DH parameters**				
	Joint	***Dn***	***THE TAn***	***Rn(mm)***	***ALPHA-n***
1	1T2	0	0	210	0
2	2T3	0	0	40	90 deg
3	3T4	0	0	210	0
4	4T5	0	0	85	0
5	5T6	140	90 deg	0	-90 deg
6	6T7	0	0	0	90 deg
7	7Tend	50	0	0	0

Table 1. DH parameters of *Epsilon-1* 7DOF surgical arm where IT2 indicates the connecting motor between 1st and 2nd joint

The figure below (Fig. 13) shows plots of step input response and sinusoidal input. The response time is quite fast; the only delay being the 10ms packet communication time on the smart servo bus. Fig 7b shows bode plots of the system and the workspace.

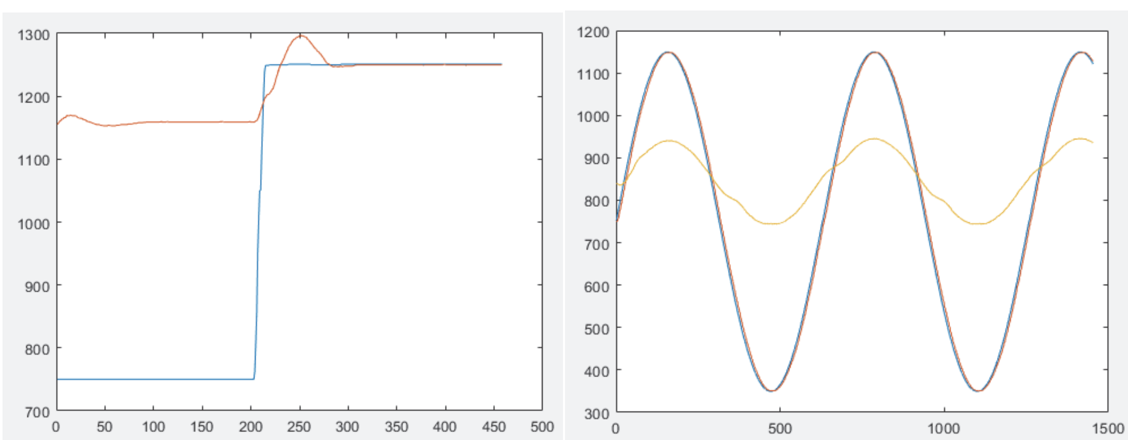


Figure 13: Force based on spring decompression to step input (left) and sinusoidal input (right) 50Hz. The orange colored line indicates the system response with a different scale factor along the vertical axis. The commanded spring decompression which corresponds to spring force is along the horizontal axis.

6.8 Limitations:

The physics engines used do not support flexible body interactions. It would be a challenging problem to implement soft body interactions with the surgical tool head and show such feedback. The feedback system is not fully complete. There is a scope of improvement of the system.

6.9 Future work and conclusions.

We plan to further improve the surgical arm setup by including a 2nd arm, which would be a mirror image, thereby constituting a dual arm setup. For example, the Da Vinci surgical systems is a large surgical manipulator operating in close and critical collaboration with a human. If it has to be further improved where the robot does surgery by itself when the AI evolves to such an extent in the future, then a form of safer compliance with a version of haptic manipulation would help and thus using an SEA motor would help in making the haptic surgical manipulator safe. We expect that the time surgeons take to transition from virtual surgery to real-world surgery using *Epsilon-1* will be minimal because the same interface that was used in the training will also be used to control the real-world surgical platform. We also show how we can assist the wounded survivors and rehabilitated them with robotic prosthesis like a robotic leg. This is the final milestone in our solution chain from rescue to rehabilitation.

7. An EMG Leg for Amputee Bikers with Gear control

So in this chapter we present the possibility of how survivors possibly from a search and rescue scenario who have lost a limb can gain some mobility with the help of a robotic leg for bike riding.Here we present our bike gear pedalcontroller prosthetic leg for helping lower limb amputees drive a motor bike and control the gear pedal of the motor bike through partial motion of muscles in the unsevered part of the legs. This is more intuitive for the driver. We also present our survey of the prosthetic legs with EMG function and describe our system to show how different it is from the existing systems

7.1 Introduction

Amputees are the people who have lost a limb in an accident or trauma or due to a disease to the limb. Nowadays there is research in build prosthetic limbs with EMG interface such that the motion of the robotic limb is with the help of muscles triggering the motion. Even if there is low limb amputation in the lower half the upper half muscles can be used in triggering and coordinating motion of the robotic prosthetic extension. Some even are drive by thought where the nerve endings at site of the amputation are used for reading signals from the brain and triggering the robotic prosthetic. One function which I have chosen from feedback of amputees who use a motorbike is they need a mechanism in their prosthetic leg to control the gears. We have a solution for the problem in the form of an EMG driven robotic leg gear controller for bikes. Here we discuss some of the EMG driven prosthetic limbs to compare how our gear controller prosthetic leg is different. There are few robotic prostheses with EMG function for example like these [141][144]. There is the bike amputee association as well who can use this contribution from us [142] and enable amputee bike riders. There have been many prosthetics with EMG function for upper limb prosthesis. For example O.W Samuel [143] et al uses pattern recognition for their multifunctional prosthesis. Hargrove et al has used EMG in gait control with nerve transfers in prosthetic leg and also Hugh Herr's [145] group at MIT Bio-mechatronics lab. There are association for amputee bicycle and motor bike riders. Some articles of custom-made mechanical legs by the amputees themselves is here [147]

7.2 Electrical Description

The central part of the electronics is the Atmel Arduino microcontroller. It connected to the EMG amplifier on an analog to digital converter port and gets real time EMG feedback. After some software threshold and timing filters it gives useful EMG values. The EMG software filter works like a switch which controls the motor driver connected to the linear actuator. When the muscles in the leg are slightly moved the microcontroller puts the linear actuator in gear change state to make the linear actuator move the robotic leg to press and release the gear pedal on the bike. There are dual IMUs in the prosthetic leg. One measures the foot posture which is driven by the linear actuator and the other measures the calf portion of the robot leg and this dual angle information is used to see if the posture of the leg is maintained so that the gear pedal can be appropriately pressed. Even if the drive moves his unsevered portion of the limb and moves the prosthetic leg the IMU information is used to maintain stable gear pedal pressing posture. The current sensor is used to measure the mechanical end stop condition or overload condition to protectively stop the leg from actuating leading to any electrical and mechanical damage. The motor drive is a PWM drive controller.

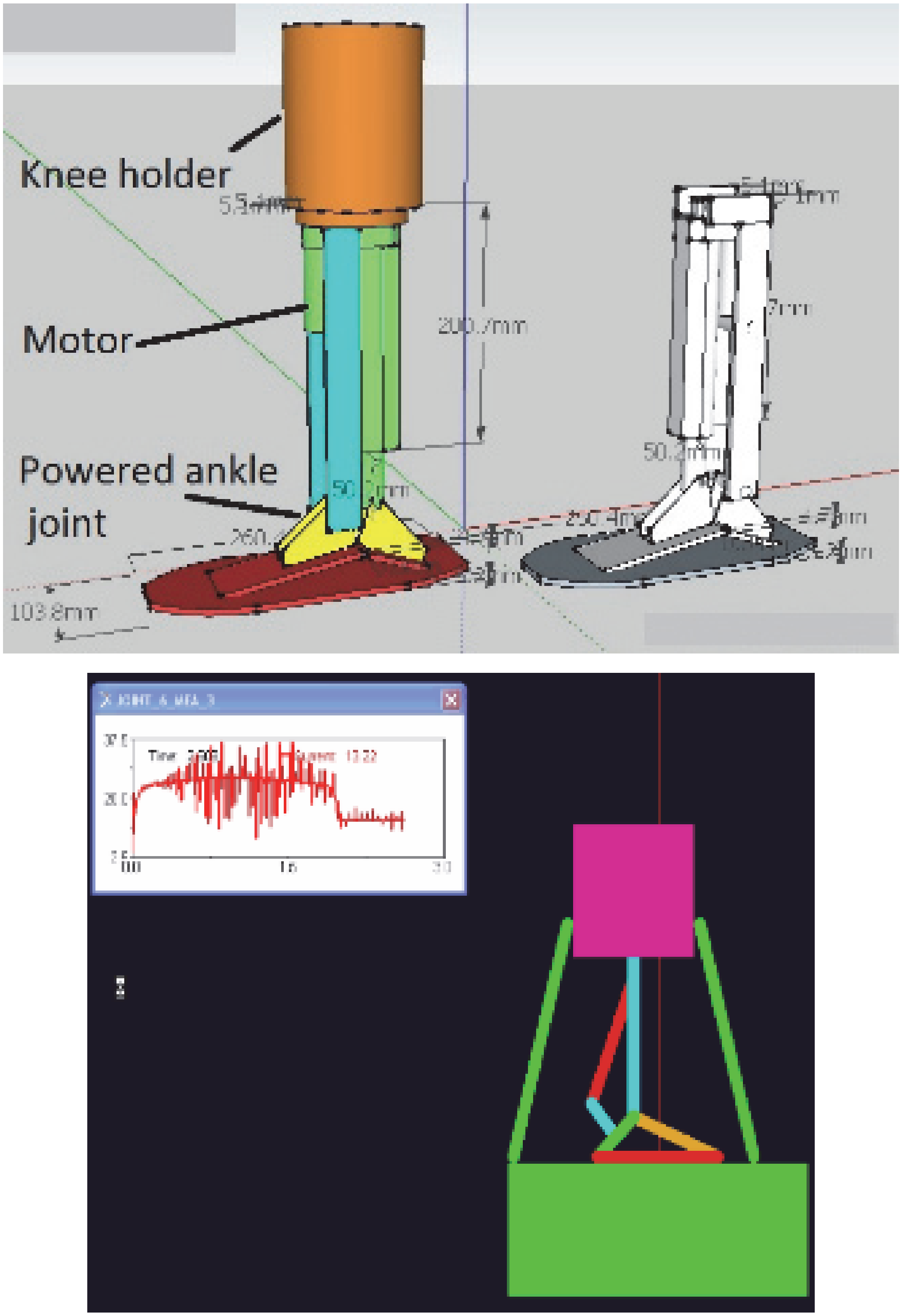


Figure 1: CAD design and load simulation of the robotic leg

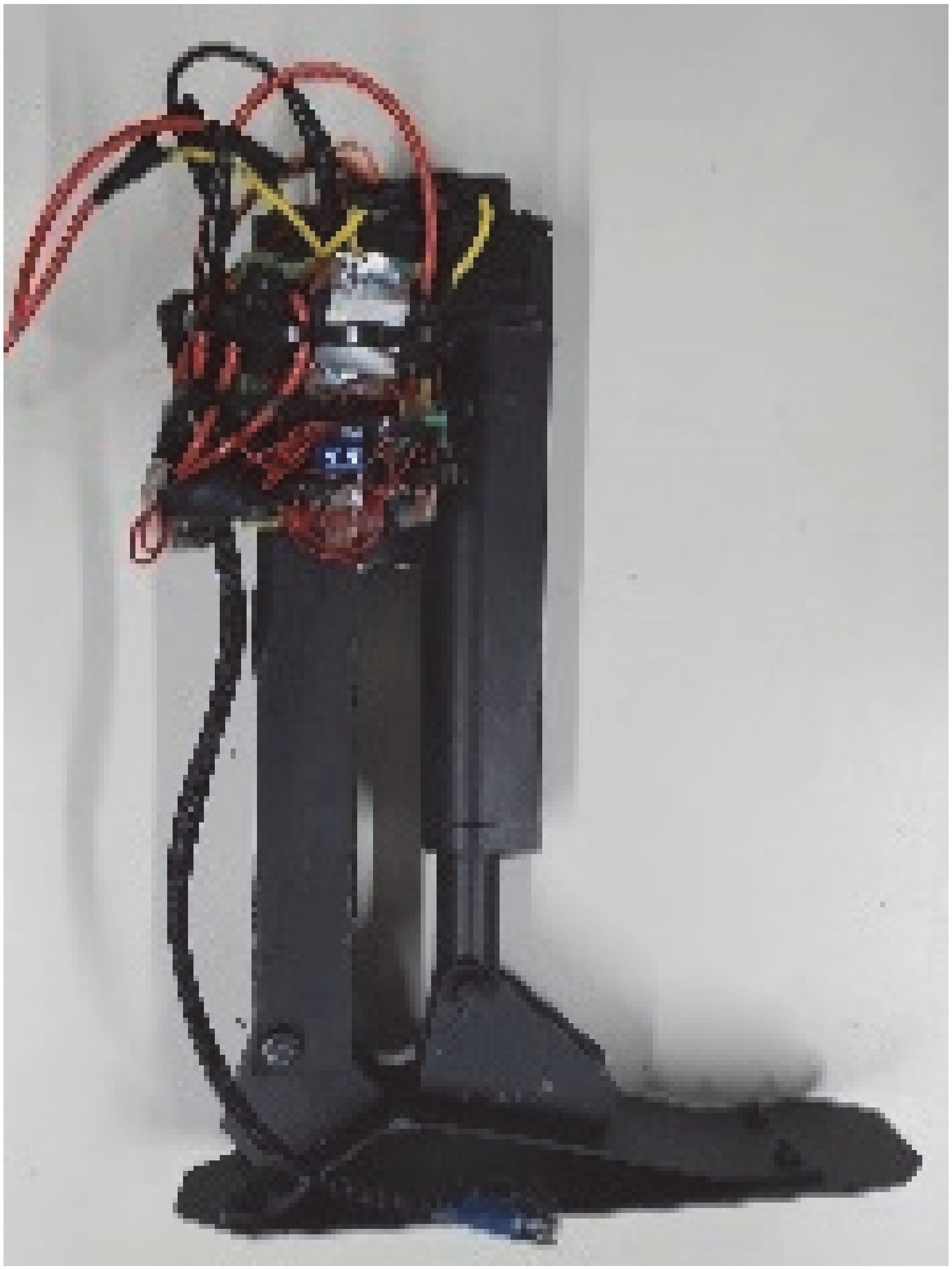


Figure 2: Prototype of the leg machined

7.3 Software description

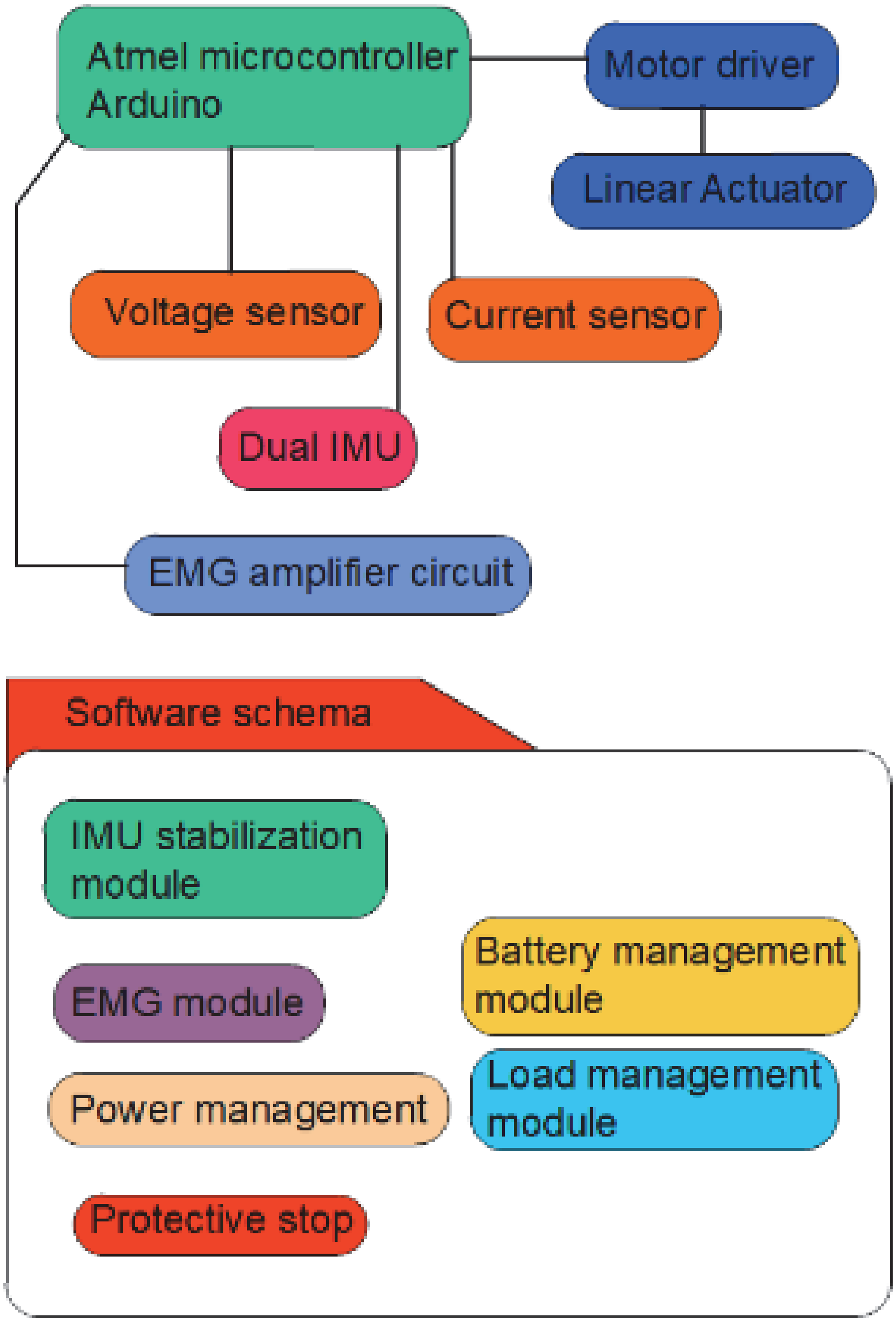


Figure 3: Embedded schema on the left and software schema on the right

The functional modules (Fig.2) of the robotic leg (Fig. 2) are as shown in the figure. The IMU module runs continuously at 30hz to calculate the foot posture angles. The motor is actuated in a way that the foot surface is always parallel to the ground and thus parallel to the gear pedal. Even if the driver changes the post of the unamputated portion of leg, the IMU module actuates the motor so that the foot is in right orientation. The EMG module continuously looks for data from the EMG amplifier. It has timer and level thresholding functions to calibrate the switching function for actuating the motor driver. There is battery management and alarm function to monitor the legs voltage requirements. There is current measurement function which monitors load on the leg and end stop conditions. We were able to stimulate the leg with hand and leg EMG signal. The biker can press the clutch of the bike with his hand, use leg triggers. Here is the demo video of the leg[146].

7.4 Limitations:

This leg was originally made with steel and is not light weight enough for walking purpose. So, to overcome the weight limitation in the future it is advisable to make it with carbon fibre or aluminium. The EMG signal processing can be further improved to overcome false positive invocation of gear shift. Sometime the process of recalibrating the sensor signal processing code block is required. It would help to auto learn the shift in the signal peak when there is an EMG trigger and machine learning might help in this in the future.

7.5 Conclusion

So, with this we have shown how we can provide an end-to-end solution chain starting from the process of search using cyborg insects, snake robots and then treating the wounded survivors with the help of doctors trained in robotic surgery and then rehabilitate the survivors with limb functionality using robotic counterparts.

Conclusion

The idea of this thesis is to provide a glimpse of one possible complete solution path from the beginning to end of the problem of search and rescue and rehabilitation. In the first chapter the cyborg insect which is a cockroach was chosen especially because unlike other insects like beetles and moths the gait of the cockroach can be controlled well to move forward or stop, to turn left or right with the help of neural stimulation signals which are commanded from the laptop end with the onboard video feedback coming from the cockroach camera. The problem with beetle is that till now there is no accurate stimulation that can control it gait like the cockroach. Currently some reseachers are working on flight modification or control of bettle through PWM stimulation wirelessly but it is not accurate. On the other hand cockroach it has been proved that its neurons can be stimulated to control the direction of its gait and is accurate. So that is the reason why we chose cockroach over a beetle for remote camera feedback based navigation. The system configuration of the cybodg insect depends on the task at hand. We need a high resolution video feedback on which we can do a controlled exploration and navigation. For this purpose also the cyborg insect needs to respond to directional stimulus. This also depends how well the cyborg cockroach responds to neural stimulation signal. And then how well we are able to calibrate its motion in response to the pulse width modulation parameters. The major requirement for the cyborg insect is whether we can do a controlled exploration with camera feedback which has not been possible before and on insects like beetle. This was achieved with our cyborg insect.

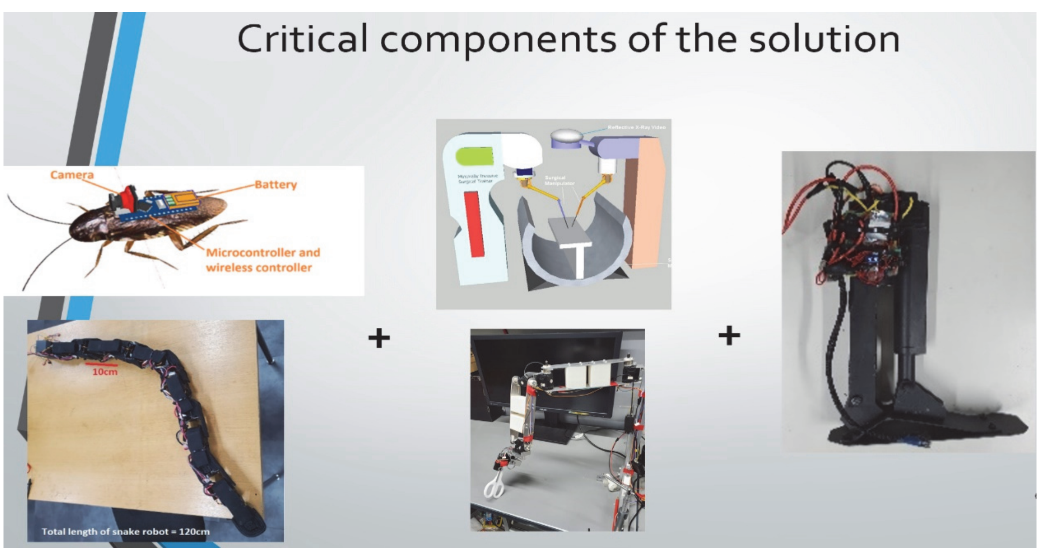
It might be possible in the future that when surgery is successful on a cockroach and when its response to stimulus is good we can bring in autonomous features like autonomous colored object tracking. We are currently using a 100mAh LiPo battery. There are many advances in battery technology these days like Sodium battery, Lithium sulphur battery, graphene based batteries which will all give improved run time for the cyborg insect but the best possible option would be a nuclear diamond battery. A nuclear diamond battery works using radioactive carbon waste (its radiation is so low that it does not affect the health of humans using it around) which can run for at least 10 years continuously. Along with application of the NDB battery that it can power cellphones in the future ,I think it will greatly benefit cyborg insects. PWM stimulation has been proven to be the most popular method to neurally stimulate an insect. All the references mentioned in this chapter/thesis/paper use a PWM signal to excite the neurons at the site of neural stimulation like the antenna and cerci in a cockroach. Because the voltage at neurons need to be beyond a certain threshold excitation potential and that is why for short duration of time a voltage pulse is applied. Some researchers have tried both positive and negative voltage pulse which is called a Biphasic signal to excite the neurons. A pulse is definitely necessary and its frequency can be varied based on the desired response during the calibration phase after the surgery. The issue with GPS is that we need a clear sky for operation and the antenna must be open to sky. It also depends on the visibility of number of satellites. In case of passive antenna there is no inbuilt mechanism to amplify the signal but in case of an active antenna there is inbuilt hardware to amplify the signal. So with active antenna the GPS will work in partially open skys, even if there is some tree coverage and near the windows. The GPS used on our cyborg insect has an active antenna and so the no.of satellites visible is also very high. And with the visibility of more satellites there is better accuracy in positioning. In case where the GPS does not work there are options to use a Bluetooth beacon with Reverse signal strength indicator with which we can get range information and if we use a directional antenna for Bluetooth along with range we can also get orientation or directional information.

The body battery of the cockroach is an interesting idea because the cockroach itself can generate energy for electronics but right now it is not practical because when turning the body of the cockroach into a battery surgery is done on the cockroach to such an extent that it cannot move. So a near long term idea would be the use of a nuclear diamond battery which will have a run time of 9-10 years. A cockroach can live for few to several weeks without eating and drinking but we provided in food and water every 4days to 1 week because the cockroach is delicate after a surgery and it needs to recover well. Initially the cockroaches after surgery were dying in one week due to insufficient ventilation in the terrarium which lead to development of fungus that killed the cockroach. But later when we improved ventilation we found that the cockroach lived well for 1.5 to 2 months. Actually for Maze navigation at the resolution of 720p we were getting about 12-15 fps. It would be possible to navigate with 6-7 fps but there is a chance the stimulation response vs joystick input one might miss a turn. The fps also depends on how sensitive the antenna of the WiFi router is. So with better infrastructure than using just a USB router one can get better range and better FPS. The input for cyborg insect is the PWM excitation signal and the output is the turning angle and stop or go forward motion.

Another robot that we tried for a search and rescue scenario is the snaker robot with sound source localization. A future work on the snake robot would be is to rebuikld another version with higher torque motors that can raise and focus beyond obstacles like small stones or rocks. This way the sound source localization will have a direct line of sight with the sound source beyond the rock and the sound source localization will not fail due to obstacles. One question raised was is it necessary to have a perfect 90 degree in the snake posture to localize in 360 deg. The answer is right now we are not using an IMU in the othergonal posture. If we use an IMU on the modules where the snake robot has microphones to perform sound source localization then a 90 degree posture is not required as the angular components can be resolves with the help of their absolute angle measurements from the IMU.

The next step is to work on the injured survivors. The idea is to use the service of the doctors who are trained in robotic surgical tools to perform surgery on the survivors. Coming to the surgical trainer arm, the bode plot is a response of the single SEA motor in the arm. It was calculated to be working at 100 Hz because of a communication packet delay which is present by default on the RS485 bus of the bioloid servo motors. To have a better response time we can try to use analog servos. The human surgery actuator response in one paper was mentioned to be around 100 -300 Hz mark. Yes this SEA based surgical arm is a haptic feedback device and yes we felt the force during the conducted tests. Right now, we have not done user feedback or user experience tests.

Coming to the final step which is rehabilitation it would be interesting to build the prosthetic robotic leg in carbon fibre and test it on real amputees. Another strategy is to use the combined sensing from the wrist and the unamputated portion of leg to initiate the actuator motion to prevernt false positives.



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Surgical simulator

Surgical arm

Robotic arm

Backpack

Sound source localization

Cross correlation

Snake robot

Hyper-redundant robot

Degrees of freedom

Haptic feedback

Series elastic actuator

Global positioning system, GPS

Thermal camera

Wireless Fidelity

Remote navigation

Sound tracking

Time delay of arrival, TDOA

Physics engine

Antennae