Development of a Masticatory Robot for Occlusal Analysis

Binsu B[1], Benyamin V. S.[2], Miriyala Durga R[3], Priam V. P[4]
[1,2,3,4]*Pillai College of Engineering*

***Abstract*— Development of masticatory robots or chewing robots is an important goal in nutrition, food science and in dental research. A masticatory robot has been proposed to reproduce the human mastication process which will help to quantitatively assess food texture changes, recording of chewing/ biting forces and testing of dental implants. The proposed masticatory robot comprises dual stepper motors which will assist in opening, closing and chewing motion of the mouth. Forces acting on teeth during chewing of food can be determined using force sensors (flexiforce sensors) placed on the upper jaw. The development of a pumping device for pumping artificial saliva along with a container for preventing food from going outside during chewing process would help in implementing a more realistic human masticatory process. The developed masticatory robot could be used for occlusal force analysis and testing of prosthetic bridges, trauma for occlusion, study of bruxism and selection of restorative material for dental implants in a cost-effective way**

***Index Terms*—Masticatory Robot, Piezoresistive film, Flexiforce sensor, food texture, Dental Implants**

I. INTRODUCTION

Mastication of food involves breakdown of food followed by the formation of bolus with the assistance of saliva. In vitro simulation of mastication is preferred in comparison to in vivo analysis of mastication as the investigation through the later process is time consuming and in vitro simulation of mastication can be carried out by using robotic devices as a platform. Masticatory robots are devices which replicate the structure and function of the human mouth [1]. In order to generate the forces between human teeth and food, development of masticatory robots is essential [2]. For dental patient training [3-4], jaw simulation [5], food texture measurement [6-7], speech therapy [8] different types of masticatory robots have been developed. These masticatory robots had limitations as they were not able to perform the 6- Degree of Freedom (DOF) mastication process mimicking the real mastication process in humans. Mastication robots with 6-DOF mastication process have been developed [2,6,9,10] but were not able to replicate the chewing behavior in the presence of saliva and mastication chamber. The 2-DOF artificial mouth developed by Salles et al. [11] mimicked real life mastication behavior and 2-DOF Artificial Masticatory Advanced Machine (AM2) [12] mimicked human chewing behavior by producing a food bolus with similar properties.

In this work, we propose a masticatory robot that comprises two stepper motors which will control the opening, closing and chewing motion of the mouth. Forces acting on teeth during chewing of food can be determined using force sensors (flex force sensors) placed on the upper jaw. Use of flex force sensors for measuring the forces acting on teeth will be a unique approach that hasn't been tried earlier. In order to prevent spilling of food outside due to the scattering and breakdown of food into several parts during the mastication process as well as to mimic the environmental conditions similar to human teeth, a container to prevent food going outside along with inlets connected to a pumping device to feed in artificial saliva.

The developed masticatory robot could be used for occlusal force analysis and selection of restorative material for dental implants in a cost-effective way

II. LITERATURE REVIEW

Different types of Masticatory robots have been developed to understand complex chewing behaviour. However, the instruments that have been developed were not able to mimic the actual mastication process instead they were able to perform few specific functions related to human mastication process. It has been an actual challenge to develop a masticatory robot that can mimic the complex mastication process involved in human beings.

A. Studies on Masticatory Robots with less than 6-DOF

WJ (Waseda Jaw) robot series were developed for dental training purposes. In order to understand the patient's mastication movements and existence forces involved during jaw opening and closing. WJ robot was developed under the assumption that the human jaw involves only 3-DOF movement [3-4], [7].

Researchers at Niigata University, Japan developed jaw simulators that could reproduce jaw open-close movement [5,13]. The first jaw simulator JSN/1C developed had one DOF and three muscle actuators [5] and the most advanced jaw simulator JSN/2A had 2-DOF and six muscle actuators [13].

B. Studies on Masticatory Robots simulated tongue, teeth and saliva with 2-DOF

The 2-DOF artificial mouth developed by Salles et al. [11] mimicked real life mastication behavior as it reproduced the functions of tongue, teeth, and saliva. The instrument developed comprised of a sealed cylinder thermostatic food cell consisting of jaws, teeth and tongue. It also consisted of a gas sampling unit and saliva injection pump to mimic the human oral physiology.

A 2-DOF Artificial Masticatory Advanced Machine (AM2) [12] was developed which mimicked human masticatory behavior. The device consisted of a temperature controlled artificial food chamber consisting of jaws and teeth as well as an artificial saliva injection pump to continuously feed saliva during the chewing process.

Shibata et al. in 2019 developed a robotic mastication simulator for food texture estimation equipped with teeth and a tongue capable of measuring biting force and tongue pressure simultaneously. Experiments were conducted to estimate the texture of doughnuts [14].

C. Studies on Masticatory Robots with 6-DOF

In order to train the patients having jaw disorders, the WY (Waseda -Yamanashi) series of robots were developed. [3-4], [15-17]. The developed robots used to operate based on gesture control i.e. when the doctor used to lower his hand or raise his hand, it would result in opening and closing of a patient's lower jaw. The developed robots were built based on parallel mechanism consisting of 6 – DOF. To reproduce the same movable range and force as a human jaw the most advanced versions, WY -5 and WY-6 consisting of parallel 6 – DOF robots were built [15-16].

Keiser et al in 2005 developed a kinematic model of the masticatory robot. The muscles of mastication were represented by linear actuators with the actuators positioned in such a way that they developed 6DOF motion for the lower jaw [6]. A robotic platform of 6RSS parallel mechanism for the lower jaw was developed which produced 6DOF motion for the lower jaw. A DC motor coupled with a crank and coupler were used to drive each RSS linkage [9]. A chewing robot based on six-bar linkage was developed to reproduce a variety of human chewing trajectories in 2D space [18].

The masticatory robot developed by Seung-Ju Lee. et al. in 2018 with the help of subminiature load cells installed at each artificial tooth of the upper jaw were used to directly measure the interaction forces between each tooth and food. The above approach enabled to analyze the different force pattern of the incisor, cuspid and molar teeth separately, and also assisted in identifying which teeth dominantly interacts with foods. The selection of linear actuators where such that they matched the human masticatory muscles with respect to size, acting force and coordination of attachment with the human counterpart [2].

D. Masticatory Robots used for testing of Dental Implants

Different studies have also been carried out in using masticatory robots for testing of dental implants which would help in determining the type of restorative material that can be used Menini et al [19]. In crowns made up of different prosthetic restorative materials a sensor-equipped masticatory robot was built in 2011 to analyze the chewing load forces. Conserva et al [20] in 2008 developed a six DOF sensor equipped mechanical chewing simulator to test the dental implants. Tahir et al [21] in 2019 developed a 6DOF robotic mastication simulator for interactive load testing of dental implants.

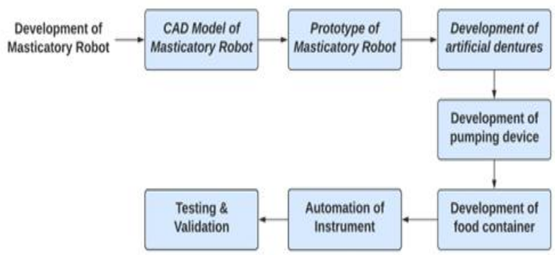
III. METHODOLOGY

A. Masticatory Robots

Mastication is a complex process whereby food taken in the mouth is converted into a bolus by mixing with saliva which is suitable for swallowing. The masticatory sequence comprises of Ingestion, Main sequence wherein food is formed into bolus through rhythmic chewing followed by clearance and swallowing.

The main sequence is modelled by a masticatory robot and its features can be measured quantitatively. We plan to build such a robot and the methodology flow chart is illustrated below in Figure 1.

Figure 1. Flow chart



In order to characterize the food dynamics and quantitatively assess food breakdown and mandibular movements during mastication, the measurement needs to be made in a continuous fashion. Based on the biomechanics of masticatory system, mathematical models have been developed to stimulate the human chewing process. However, it is difficult to develop mathematical models for assessing masticatory efficiency due to numerous variations in food properties and structures of human jaws, hence development of masticatory robot is essential which can reproduce the mastication process in a repeatable and mechanically controllable way to quantitatively access the masticatory efficiency and food dynamics. The three major muscles responsible for the masticatory movements are temporalis, masseter and pterygoid. Development of masticatory robot is helpful as it assists in collection of detailed information pertaining to the forces applied during mastication and dynamics of food breakdown. To quantitatively evaluate the dynamic changes to the texture of foods during chewing the information gathered during mastication process would be helpful.

IV. DEVELOPMENT OF INSTRUMENT

A. Design Iterations of Masticatory Robot

1) Iteration 1: A basic static CAD model of the masticatory robot is shown in Figure 2 below. The goal is to actuate the opening, closing and chewing motion with the help of single stepper motor and 4-bar linkage mechanisms. The upper jaw is adjustable, whereas the upper jaw is movable. The stepper motor coupled with the bevel gear arrangement drives the 4-bar linkage mechanism attached with lower jaw which will help in opening and closing movement of the mouth and the 4-bar linkage mechanism coupled with bevel gear and rack and pinion arrangement will assist in oscillatory motion of the lower jaw with the help of axial thrust bearing. The synchronous motion of both the linkage mechanisms will assist in chewing motion of the lower jaw with respect to the upper jaw.

a) Demerits of Design: The Design is too bulky with the setup volume of 850 x 850 x 455 mm. Only chewing motion is possible in the existing design. A high-torque stepper motor would be required.

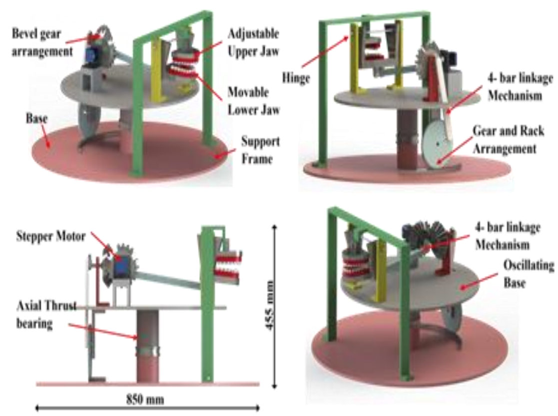


Figure 2. Basic Static CAD model of single motor Masticatory Robot with linkage mechanism

2) Iteration 2: A basic static CAD model of the masticatory robot is shown in Figure 3. The goal was to actuate the opening, closing and chewing motion with the help of single stepper motor and gear train. The upper jaw is adjustable, whereas the lower jaw is movable. The stepper drives the gear train which assists in rotary motion of the central gear, thus enabling the rotary motion of the cam thereby helping in opening and closing movement of the mouth and the lower gear in gear train is coupled with bevel gear which will assist in oscillatory motion of the lower jaw with the help of Rotary to Oscillatory Mechanism. The synchronous motion of the entire system will assist in chewing motion of the lower jaw with respect to the upper jaw. The design is much compact as compared to the first design.

a) Demerits of Design: Only chewing motion is possible in the existing design. A high-torque stepper motor would be required.

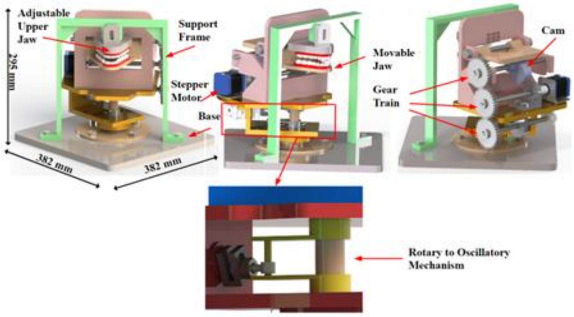


Figure 3. Basic Static CAD model of single motor Masticatory Robot with Gear Train and Cam Shaft Mechanism

3) Iteration 3: A basic static CAD model of the masticatory robot is shown in Figure 4. The goal is to actuate the opening, closing and chewing motion with the help of two stepper motors. The stepper motor 1 coupled with the camshaft will help in opening and closing movement of the mouth and the stepper motor 2 will convert the rotary motion to oscillatory motion which will help in providing oscillatory motion to the lower jaw. When only opening and closing motion of mouth is required Stepper motor 1 will be turned on and synchronous motion of Stepper motor 1 and Stepper motor 2, we will achieve the chewing motion.

a) Demerits of Design: The design is bulky as compared to the earlier one.

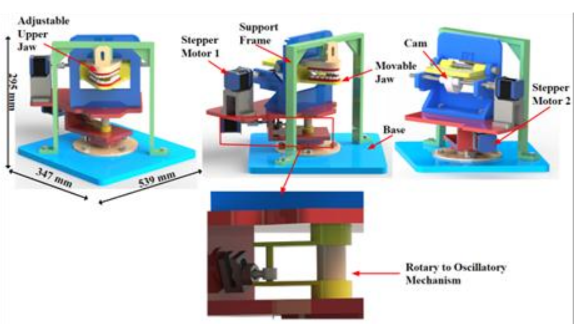


Figure 4. Basic Static CAD model of dual motor Masticatory Robot

E. Design and Fabrication of the Instrument

1) Actuators: A basic static CAD model of the masticatory robot is shown in Figure 5. The goal is to actuate the opening, closing and chewing motion with the help of two stepper motors. The stepper motor 1 coupled with the camshaft will help in opening and closing movement of the mouth and the stepper motor 2 will convert the rotary motion to oscillatory motion which will help in providing oscillatory motion to the lower jaw. When only opening and closing motion of mouth is required Stepper motor 1 will be turned on and synchronous motion of Stepper motor 1 and Stepper motor 2, we will achieve the chewing motion.

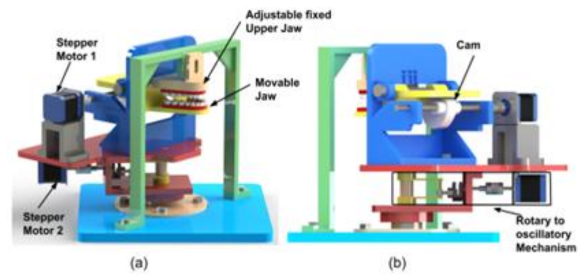


Figure 5. Basic CAD model of Masticatory Robot, showing only the positions of the actuators relative to the mouth (a) Isometric Front View (b) Isometric back View

2) Sensors: A provision for positioning of the piezoresistive film on the upper jaw will be made. So that it can be used for recording the forces acting on each tooth. As the forces recorded by the sensor will be small hence a signal conditioning amplifier will be required. However, if there is a space constraint for placing all the piezoresistive film on each tooth of the upper jaw then the next plan is to use flexiforce sensors which can be used for recording the forces.

3) Instrumentation: Since simultaneous measurements of many variables (force, displacements, voltage) are required we will use a 16-bit Ni DAQ real time data acquisition system to measure the force and moments as well as to control the motion of the various stages. All the different components like forces, linear actuators, motors, data acquisition system etc. will be collected in LabVIEW software. In addition, we will also use LabVIEW to control a peristaltic pump to pump artificial saliva into the chamber

4) Chamber Design: There will be a provision for building a food chamber which will hold the chewed food particles inside the mouth as well as to pump artificial saliva to the mouth. The prototype of the masticatory robot will be custom fabricated using our in-house 3D printers, laser cutting machine and table top CNC milling machine.

5) Testing and Validation: Once the masticatory robot with artificial dentures is automated the next step is to analyze the different textures of food and compare the forces recorded with an in vivo observation. The developed instrument can be also used for occlusal analysis using T-scan novus sensor. The developed instrument will be also used for testing of dental implants that will help in deciding the type of restorative material to be used for dental implants.

F. Initial Work done in the proposed Development of Technology

1) Prototype of 1-DOF instrument: A 1-DOF instrument has been developed to simulate the mechanics of a single tooth [26]. A single tooth made up of stainless steel with diameter of 8mm and height of 12 mm is fastened on a movable bed (3d printed) which acts as the lower jaw. A flex force sensor is used for occlusal analysis. Movable bed has a brass nut fastened to it on which the threaded shaft slides through it which acts as a nut and bolt arrangement. Stepper motor mounted on the acrylic plate is coupled with the threaded shaft which allows the movable bed to move in upward and downward direction. The movable bed is guided by guide rods through linear bearings press fitted at the ends of the movable bed. The acrylic plate is supported by support rods and the entire setup is rested on a wooden base as shown in Figure 6 below.

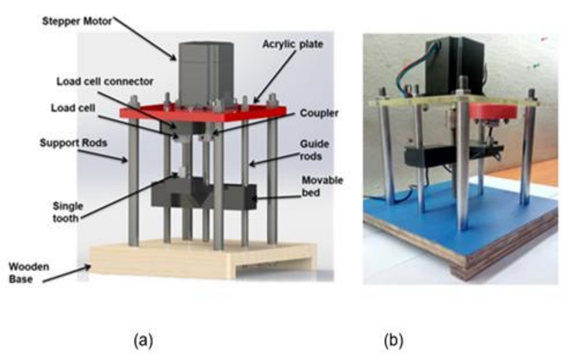


Figure 6. (a) 1-DOF Instrument Design (b) Developed 1-DOF Instrument

2) Force Measurement with flexiforce sensor: Flexiforce sensor is connected to the flexiforce prototyping kit for recording the readings through the microview demo software. The kit is placed on a movable bed arrangement as shown in Figure 6 (a). The height of the Adjustable bed can be adjusted to a particular height based on the location of the tooth as shown in Figure 6 (a). The flexiforce prototyping board consists of RGB LED bulb. When RGB LED bulb glows red it means the flexiforce sensor has reached its peak value. Once the RGB LED bulb glows red then the movable bed in the setup is made to travel in the downward direction by manually pressing the toggle switch which makes the stepper motor to rotate in the reverse direction and thereby making the movable bed to come downwards.

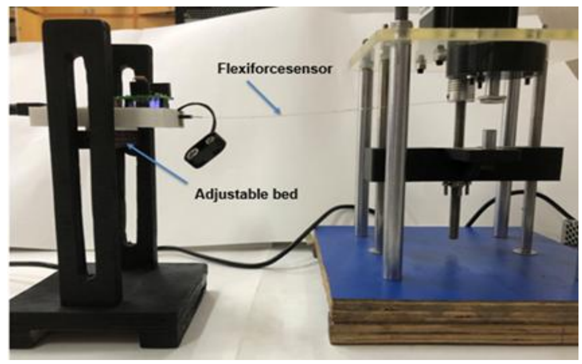


Figure 7. Connection of Flex force sensor with setup

3) Interfacing of Stepper Motor Control and Flex force sensor using NI-USB 6001 DAQ: The Flexiforce sensor is positioned between the tooth attached to the adjustable bed and movable bed in the final automated dental occlusal system. The entire system is automated using a code developed in LabVIEW. The movable bed moves in upward and downward direction through the stepper motor interfaced with NI-USB 6001 DAQ through motor driver. The data received from flex force sensor is amplified using an inverting Op-amp. This amplified signal is passed onto NI- USB 6001 DAQ for data acquisition. Both Stepper Motor and flexiforce sensor has been interfaced using NI-USB 6001 DAQ. This has assisted in controlled the entire system through Data acquired via NI-USB 6001 DAQ.

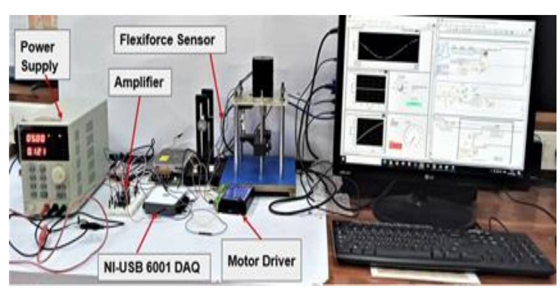


Figure 8. Interfacing of Stepper Motor and Flexiforce sensor with NI-USB 6001 DAQ

4) Wire Diagram: As observed in Fig. 9. the flexiforce sensor is connected to the analog input of NI-USB DAQ 6001 via inverting Op-Amp and the direction and stepper wire of motor driver is connected to digital input of NI-USB DAQ 6001. RMCS 1102 motor driver is connected with Nema 23 Stepper motor for motor control, supply to motor driver is provided by power supply (SMPS).

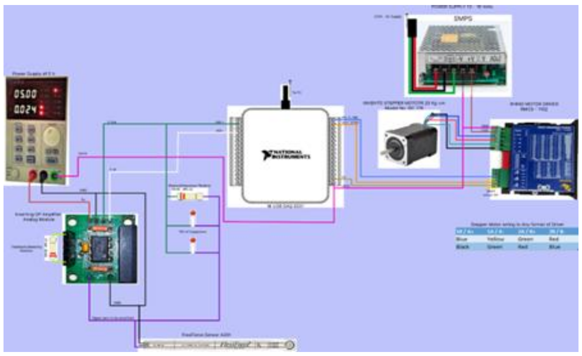


Figure 9. Wire Diagram

V. CALIBRATION OF FLEXIFORCE SENSOR A201-1

Calibration of flexiforce sensor includes two major steps (1) Sensor conditioning (2) 3 – point linear calibration.

1) Sensor Conditioning- It is done by applying 120% of the expected maximum force 3 – 5 times at an approximately equal duration of time. The circuit sensitivity is adjusted by adjustin the potentiometer.

2) 3-point Calibration – Apply and plot a low, medium and high load, then record circuit output for each. Loads are reapplied to verify calibration.

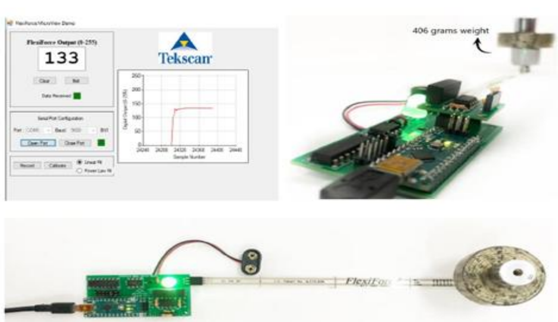


Figure 10. Conditioning the sensor

The flexiforce sensor was calibrated by placing known standard weights in an increemental order. The flexiforce sensor used is A201-1. The A201-1 has a range of 1lb however it can be used for weights upto 1kg. Table 1 shows the digital output received from microview demo softwareon application of known standard weights in an interval of 50 gms. A graph of digital output vs applied load (known weight) shows a linear relation as shown in Fig. 11.

Table 1 – Digital Output vs Load

Sr. No.	Load in grams	Digital Output	Sr. No.	Load in grams	Digital Output
1	50	10.18	10	506	156.83
2	105	29.61	11	556	178.94
3	151	44.22	12	606	199.65
4	200	61.83	13	656	195.69
5	250	74.49	14	706	207.88
6	300	100.19	15	756	217.75
7	350	110.59	16	806	249.52
8	406	125.06	17	810	252.42
9	456	144.66	18	820	255

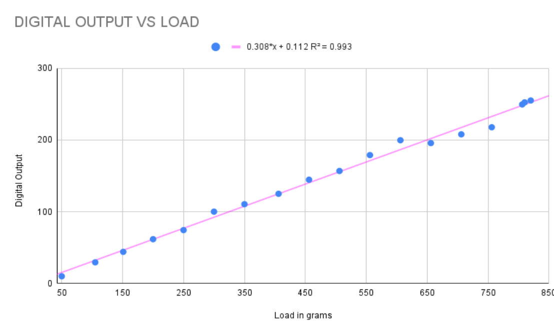


Figure 11. Graph of digital output vs load in grams

VI. CONCLUSION

The developed one degree of freedom occlusal system will help in measuring the occlusal bite force for a pair of tooth as shown in Fig.12.

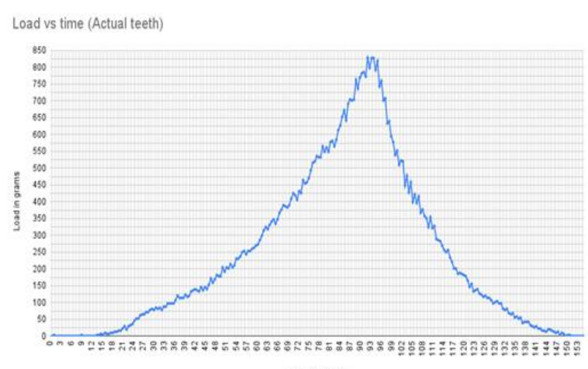


Figure 12 – Graph of load vs time

The developed in-vitro masticatory robot as shown in Fig. 5 could be used to measure the forces acting on teeth during chewing of food. The developed masticatory robot could be used for occlusal force analysis and testing of prosthetic bridges, trauma for occlusion, study of bruxism and selection of restorative material for dental implants in a cost-effective way

ACKNOWLEDGMENT

The Development of one DOF Occlusal Analysis System was supported by University of Mumbai. Minor Research grant APD/ICD/2019-20/762. This work is part of the "Development of an In Vitro Instrument for Occlusal as well as Chewing Force Analysis and Testing of Dental Implants" project, funded by Anusandhan National Research Foundation (ANRF) under Core Research Grant funding with project reference number CRG/2023/004519. Thanks to Pillai College of Engineering in providing support by utilizing the facilities under Makers Studio, Innovation and Research Center.

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