Biorobotics Project Proposal

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Abstract

Starfish locomotion is provided by a combination of limb motion and the coordinated movement of thousands of adhesive microstructures called tube feet. For this project we propose a starfish inspired robot, with gecko like adhesive surfaces that will allow its motion in a similar way as tube feet do for biological starfish. This robot will be tested in different surfaces and slopes, in dry and underwater conditions. We expect to achieve a robust path following planar motion and strong adhesion to surfaces to allow the robot to attach and crawl in a consistent way regardless the type of surface encountered.

I. Introduction

Research in underwater robot locomotion has increased in the last decades, achieving a successful interaction with the environment for heavy duty tasks such as deep sea exploration, pick and place large and heavy objects, pipeline inspection and maintenance and the extraction of mineral resources [1], [2]. Most of these underwater robots have rigid bodies and are actuated with electrical motors or hydraulic circuits [2] which satisfy the mobility and dexterity requirements for the previously mentioned tasks. However, there are other relevant underwater tasks that are still done manually and require a more flexible gait in order to be done accurately, eg. biological sample gathering, archaeological exploration, underwater exploration of otherwise inaccessible areas, etc. [1] These kinds of tasks require a soft, flexible robot capable of maneuvering across different surfaces underwater.

Sea creatures provide of multiple gait and motion techniques combined with flexible structures, that allow them to move in different and efficient ways [3], [4], [5], this has been widely studied and served as inspiration for different kinds of underwater mobile soft robots like swimmers [6], [7], [8], walkers [9], [10], crawlers [11] or a combination of these[12], [13].

Inspired by the sea-star locomotion, many attempts have been made to create a sea-star crawler [14]. However, most of the starfish robot gaits are based on inchworm locomotion [15], [16], [17], [18], [6], [19]. These studies have not taken into consideration the ‘tube-feet’, shown in figure 1.b , which are unique organs for the echinoderm family that provide sensing capabilities, contribute to feeding, allow the sea-star to grip onto various surfaces and contribute to its locomotion [20], [21]. Those studies that have considered these microstructures rely heavily on external systems to manipulate the sea-star [22], [23], although recent progress has been reported with the use of magnetic fields for actuation [22] and adhesion [23], still starfish inspired locomotion has not shown precise path following [6], [19], [22]

Geckos, on the other hand, have nano-fibrillar structures on their feet as shown in figure 1.e and 1.f that allow them to adhere to multiple types of surfaces without any tackiness by means of weak van der Waals forces, thus enabling them to walk vertically and even upside down [24]. Based on this mechanism, many adhesive surfaces have been fabricated for applications in soft grippers [25], [26], [27], wall climbing robots [28], [29] etc.

However, sea-star locomotion has not been combined with the gecko adhesion to enable the robot to have an inchworm-like locomotion underwater. Thus, we plan to investigate if the addition of the gecko-inspired adhesive surface to a soft, flexible sea-star inspired locomotion robot improves its ability to grip on various surfaces and contribute to more robust motion control.

II. Research Question

The research question that we are addressing in this project is: Will the addition of gecko inspired adhesion give a mobile starfish inspired robot a better grip to different kinds of surfaces, thus giving it a precise path following motion? Our hypothesis is that gecko inspired addition will give the robot a better

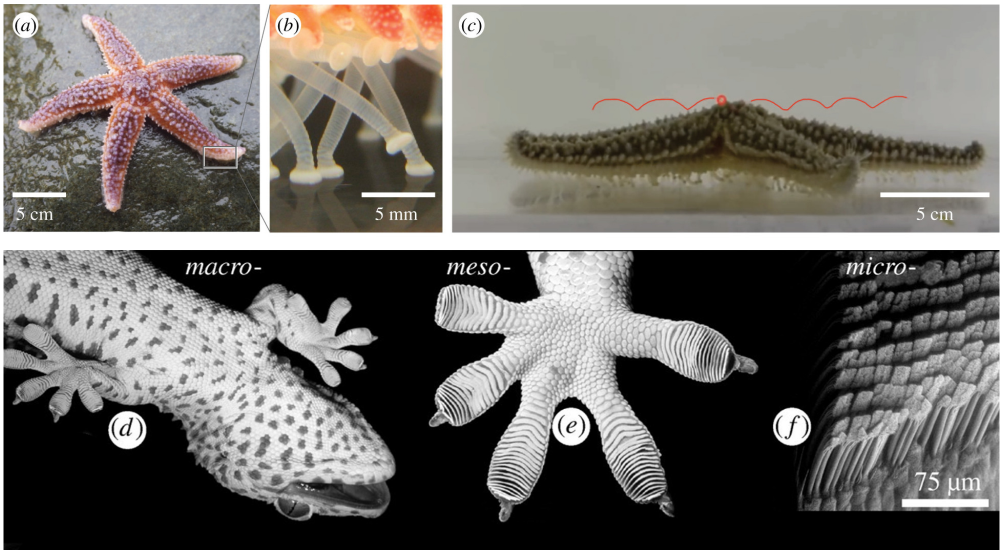

Fig. 1. Bioinspiration Images (a) Common sea star Asterias rubens (b) Tube feet of the sea star, (c) Sea star gait description. Ref: [21] (d) Ventral view of a tokay gecko (Gekko gecko). (e) Tokay gecko foot, showing array of seta-bearing scansors. (f) Microscale array of setae. Ref [30].

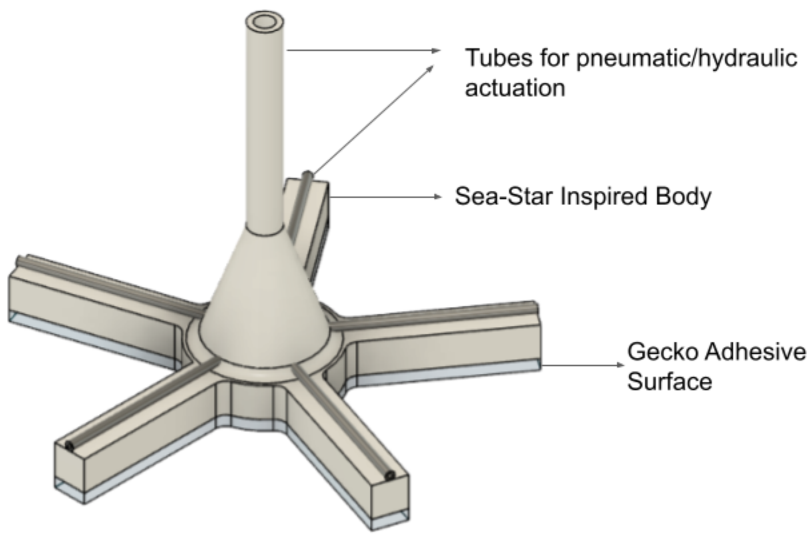

Fig. 2. CAD rendered model of our proposed robot.

grip than current starfish inspired robots and it will contribute to a better locomotion strategy for path following.

III. Preliminary Design

The proposed robot will have a soft and flexible biomimetic structure, inspired by the starfish as shown in figure 2.

The system under focus will be classified into subsystems based on the functionality of the specific contrivance that is being used predominantly. These Subsystems are Locomotion, Control, Perception, Actuation and Energy.

Locomotion primarily concerns the body configuration (Dynamic constraints) during movement while actuation is the switch between Gaits/Animal behaviors.

The subsystems are to be designed as follows. The Locomotion subsystem is a Bi-pedal crawler which relies heavily on the starfish “Feet” for its movement. Each foot consists of a radial fixed link (Cylinder) with 5 slots. Each slot has a piston that will be actuated either Hydraulically or Pneumatically. These pistons can be designed to be either interlinked or independent based on experimentation results. The feet have a layer of ‘Gecko Adhesive’. This is a material with directional properties and is used to replicate the adhering mechanism seen in a Gecko. This is the cross-gait actuation that is explained later. The Gecko tape forms the second of 2 layers. The upper layer is the mechanism. The pistons provide the sliding motion after the tape under a slot disengages. The disengagement is driven by a simple Clutch/Servo system as the tape can be adhered(lowered) using servo and actuated piezo electrically or pneumatically to change shape. This allows it to conform better to the surface, thus facilitating superior grip between the surface and the engaged potion of the robot. The five cylindrical system is designed so as to provide added control while elevation changes. In any condition, at least 2 of the 5 Cylinders will be engaged (Adhered to the surface). A pentagonal configuration also provides stability and allows for adequate degrees of freedom. As reverse motion can be derived as some combination of the other 5 links, it has been removed to allow control simplicity. Because the Robot has greater degrees of freedom than actuators, it is an under actuated system. The cylindrical ensemble is complemented by striations protruding out. These are for mainly sensory purpose and might be implemented as part of the starfish gait (Allows separate Nano-tentacles to move using flow of water as a trigger)*. Between the Stick-able patches, there are sensors embedded.

The control subsystem is mainly for implementing the locomotion. Control in this case is broadly divided into 2 parts. Locomotion control and process control. Process control deals with the incoming data from sensors (To assess the shape, conformity and possibly the coefficient of friction/Wetness of surface). This determines the movement strategy based on Force and movement angle. The Locomotion control deals with the Radial mechanism actuation. This actuation can be achieved by a Brushless DC motor (BDC) or Servo motor using a clutch. The Clutch controls which links are actuated. The Pneumatic system is for mechanical advantage and will be triggered by a BDC/Servo.

The actuation subsystem deals with controlling the engage and disengage action for the gecko feet. All 3 have separate controllers based on separate behaviors. A Raspberry Pi will be used for interface and control. In addition, all motors are coupled with motor drivers to enable ease of handling. Perception uses sensors to gauge the shape, elevation and conformity of the terrain under consideration.

The perception subsystem is interfaced using Arduino and its main function is data acquisition and processing from the robot’s sensors. Force sensors will be located between the Gecko Patches and robot structure for contact sensing. An Inertial Measurement Unit (IMU) will be used for pose and position estimation and resistive bend sensors will gather information about the robot’s limbs relative position to the structure.

Energy subsystem is conformed by the robot’s power supply and the components and structure related to its distribution to all required robot’s components: actuators, sensors and controller.

IV. Narrative Description of the Project Plan

We propose to build a soft flexible, starfish inspired robot, which will be actuated with a pneumatic or hydraulic system. For this we will start with a design phase, where the main robot’s subsystems will be designed: Structure, Electronics, Actuation and Controls. The structure will be designed in order to give the robot the necessary flexibility and compliance to interact with irregular surfaces. Control system design will play an important role in this stage in order for the robot to move according to our purpose. After completion of this stage, and with the detailed design of the robot ready, we will start a fabrication phase, where the robot will be fabricated using available equipment from TechSpark, Soft Machines Lab and [Sampada’s Lab]. We expect this phase to last about 25 days. Once the robot has been fabricated and all subsystems integrated into it, we will start the testing phase, with in laboratory testing for specific elements of the robot and ”field” testing in a water tank.

On the other hand, we propose to use gecko inspired adhesion for the starfish's tube feet. We will be fabricating our own gecko adhesive and testing it for underwater adhesion. In case this doesn't work as expected, we can get commercially available gecko tape.

V. Planned Experiments

Based on the starfish robot, several experiments will be conducted to measure the performance of the robot. The performance test will be divided into two parts: adhesion and motion. A force meter with spring measures the maximum pull forces the Starfish-based Gecko-adhesive Robot can exert under dry and underwater environment respectively, and compare with similar robots. To assess the robot motion, a camera is installed on a bracket to capture the robot locomotion gaits and positions under different time step. The robot will be tested on different terrains like flat, rugged, inclined and vertical. All the images will be post-processed to measure the deviation from the planned path and calculate the motion precision. In addition, data received from force sensors and IMU will be used to estimate the performance of robot motion.

A. Adhesion Performance

The first experiment is designed to test the adhesion of the gecko-inspired adhesive patch. One spring tip of the force meter is fixed on the static robot and another tip is connected to the Universal Tensile Test machine. The machine will exert a stably increasing force. The robot will experience the dragging force and the reading of this force will be shown on the force meter. Test will be carried out until the patch slips.

The test will be conducted in dry and underwater environments in three directions. The longitudinal direction (x), lateral direction (y) and vertical direction (z). The robot will be tested 10 times in each direction to get the average value of friction and eliminate the outliers. Results will be compared to reported results from literature to evaluate the robot's performance.

B. Motion Performance

The second experiment is to evaluate the successful execution of the robot locomotion subject to different terrains. The robot will be tested on different terrains and slopes. The characteristic of the surfaces will be quantified by Root Mean Square (RMS) of sampling points. A camera will be placed above the robot held by a bracket. While the robot is moving forward along a pre-defined path, the camera will record its motion. We will use computer vision processing to calculate the deviation between the actual path and planned path for each trial. Using the data from the IMU, the robot's posture (x, y, z, roll, pitch, yaw) and gaits can be estimated and checked whether it is within an acceptable range. Finally, energy consumption will also be recorded upon finishing the whole trial. These experiments will be run in series and the results obtained will be compared to reported results from literature.

C. Summary List of Preliminary Experiments

- **Adhesion** Connect Starfish-Gecko robot with UTT machine and record the maximum Reference adhesion force along longitudinal direction(x), lateral direction(y), vertical direction(z) on a standard dry surface.
  Repeat above experiments on the surfaces with different roughness, and underwater environments.
- **Motion** Camera cross-track actual path of robot on flat, rugged, inclined and vertical terrains. Calculate deviation between actual path and planned path.
  Export robot posture data and compare them with references to evaluate its performance.
- **Water Tightness** Robot's structure will be tested to ensure that water will not enter and damage any internal components. Testing will be done with pressurized air and underwater in a water tank.

- **Operational Testing** All robot's subsystems will be tested in order to evaluate their functionality. These will be held in laboratory environment, previous to the integration to the robot and once integrated. Some tests that will be done: Sensor data acquisition, actuator motion, structure's flexibility and sturdiness, etc.

VI. Individual Technical Contributions

- **Sampada Acharya:** Responsible for the material science aspect of the robot and modelling. Specific tasks:
  1) Gecko adhesive design, modelling and fabrication.
  2) CAD modelling.
- **Peize Hong:** Responsible for the robot's control. Some of his tasks:
  1) Control algorithm design and modelling.
  2) Control subsystem implementation.
- **Viraj Ranade:** Responsible for general coding and algorithm design and implementation. Among some specific tasks, there is:
  1) Machine-Learning for motion control and path following optimization.
  2) AI based techniques and modelling the collected data.
- **Peter Roberts:** Responsible for mechanical design and fabrication and systems integration. Some specific tasks:
  1) Mechanical structure and actuators design.
  2) Mechanical modelling.
- **Raghav Singhal:** Responsible for the electronics and sensoring areas of the project. Some of the main tasks are:
  1) Sensor selection, implementation and sensor data processing.
  2) Electronic design.

VII. Tentative Schedule

Appendix A shows the project's proposed Gantt Chart, showing the main tasks to be completed and the team member responsible of its execution.

VIII. Stretch Goals

If our project develops as planned, there are four other points that we expect to cover:

- **Make it smart:** The robot will be able to make decisions on the best locomotion strategy based on the localized topography roughness of the terrain.
- **Obstacle interaction:** The robot will be able to detect obstacles in its path and choose an interaction strategy: avoiding the obstacle or climbing it.
- **Path planning:** The robot will be able to sense its surrounding terrain within a reasonable range and decide on the path to optimize its trajectory.
- **Limb motion:** The robot will make use of the motion of its limbs for directed locomotion.

IX. Budget

The project's estimated budget is a total of $970.00 and the detailed description can be seen in Table I.

Category	item	Cost
Materials	Gecko Tape	$30.00
Materials	Diffraction grating	$20.00
Materials	Submersible water pump	$24.00
Materials	Tubing	$20.00
Materials	Smooth-On Ecoflex 00-30 Silicone	$66.00
Materials	Sylgard PDMS	$150.00
Materials	Valves	$30.00
Materials	Syringes	$20.00
Materials	Miscellaneous hardware and mounting elements	$50.00
Electronics	Raspberry Pi 4 Model B (8GB RAM	$50.00
Electronics	Micro HDMI to HDMI Adapter	$10.00
Electronics	IMU Sensors	$15.00
Electronics	Flex sensors (FSR)	$60.00
Electronics	Power supply	$5.00
Electronics	Force sensors	$35.00
Electronics	Servo motors	$25.00
Electronics	Servo motor shield	$20.00
Electronics	Miscellaneous electronic components	$50.00
Fabrication	3D printing/Laser cutting equipment cost	$190.00
Testing	Characterization (SEM)	$100.00
	Total	**$970.00**

TABLE I
DESCRIPTION OF MAIN ITEMS INCLUDED IN THE PROJECT'S BUDGET.

REFERENCES

[1] Z. Wang and W. Cui, "For safe and compliant interaction: an outlook of soft underwater manipulators," *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, vol. 235, no. 1, pp. 3–14, 2021.

[2] J. Neira, C. Sequeiros, R. Huamani, E. Machaca, P. Fonseca, and W. Nina, "Review on unmanned underwater robotics, structure designs, materials, sensors, actuators, and navigation control," *Journal of robotics*, vol. 2021, pp. 1–26, 2021.

[3] B. J. Gemmell, S. P. Colin, J. H. Costello, and J. O. Dabiri, "Suction-based propulsion as a basis for efficient animal swimming," *Nature communications*, vol. 6, no. 1, pp. 8790–8790, 2015.

[4] X. Mo, W. Ge, M. Miraglia, F. Inglese, D. Zhao, C. Stefanini, and D. Romano, "Jumping locomotion strategies: From animals to bioinspired robots," *Applied sciences*, vol. 10, no. 23, pp. 8607–, 2020.

[5] *Bioinspired sensing, actuation, and control in underwater soft robotic systems*, 1st ed. Cham, Switzerland: Springer, 2021.

[6] Z. J. Patterson, A. P. Sabelhaus, K. Chin, T. Hellebrekers, and C. Majidi, "An untethered brittle star-inspired soft robot for closed-loop underwater locomotion," in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2020, pp. 8758–8764.

[7] C. C. Ulloa, S. Terrile, and A. Barrientos, "Soft underwater robot actuated by shape-memory alloys "jellyrobcib" for path tracking through fuzzy visual control," *Applied sciences*, vol. 10, no. 20, pp. 7160–, 2020.

[8] Q. Shen, Z. Olsen, T. Stalbaum, S. Trabia, J. Lee, R. Hunt, K. Kim, J. Kim, and I.-K. Oh, "Basic design of a biomimetic underwater soft robot with switchable swimming modes and programmable artificial muscles," *Smart materials and structures*, vol. 29, no. 3, pp. 35 038–, 2020.

[9] Q. Wu, X. Yang, Y. Wu, Z. Zhou, J. Wang, B. Zhang, Y. Luo, S. A. Chepinskiy, and A. A. Zhilenkov, "A novel underwater bipedal walking soft robot bio-inspired by the coconut octopus," *Bioinspiration biomimetics*, vol. 16, no. 4, pp. 46 007–, 2021.

[10] F. Corucci, M. Calisti, H. Hauser, and C. Laschi, "Evolutionary discovery of self-stabilized dynamic gaits for a soft underwater legged robot," in *2015 International Conference on Advanced Robotics (ICAR)*. IEEE, 2015, pp. 337–344.

[11] Q. Tan, Y. Chen, J. Liu, K. Zou, J. Yi, S. Liu, and Z. Wang, "Underwater crawling robot with hydraulic soft actuators," *Frontiers in robotics and AI*, vol. 8, pp. 688 697–688 697, 2021.

[12] F. Giorgio-Serchi, A. Arienti, F. Corucci, M. Giorelli, and C. Laschi, "Hybrid parameter identification of a multi-modal underwater soft robot," *Bioinspiration biomimetics*, vol. 12, no. 2, pp. 025 007–025 007, 2017.

[13] A. Arienti, M. Calisti, F. Giorgio-Serchi, and C. Laschi, "Poseidrone: Design of a soft-bodied rov with crawling, swimming and manipulation ability," in *2013 OCEANS - San Diego*. MTS, 2013, pp. 1–7.

[14] S. M. Youssef, M. Soliman, M. A. Saleh, M. A. Mousa, M. Elsamanty, and A. G. Radwan, "Underwater soft robotics: A review of bioinspiration in design, actuation, modeling, and control," *Micromachines (Basel)*, vol. 13, no. 1, pp. 110–, 2022.

[15] R. F. Shepherd, F. Ilievski, W. Choi, S. A. Morin, A. A. Stokes, A. D. Mazzeo, X. Chen, M. Wang, and G. M. Whitesides, "Multigait soft robot," *Proceedings of the National Academy of Sciences - PNAS*, vol. 108, no. 51, pp. 20 400–20 403, 2011.

[16] S. Mao, E. Dong, M. Xu, H. Jin, F. Li, and J. Yang, “Design and development of starfish-like robot: Soft bionic platform with multi-motion using sma actuators,” in *2013 IEEE International Conference on Robotics and Biomimetics (ROBIO)*. IEEE, 2013, pp. 91–96.

[17] S. Mao, E. Dong, H. Jin, M. Xu, and K. H. Low, “Locomotion and gait analysis of multi-limb soft robots driven by smart actuators,” in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, vol. 2016-. IEEE, 2016, pp. 2438–2443.

[18] S. Mao, E. Dong, H. Jin, M. Xu, S. Zhang, J. Yang, and K. H. Low, “Gait study and pattern generation of a starfish-like soft robot with flexible rays actuated by smas,” *Journal of bionics engineering*, vol. 11, no. 3, pp. 400–411, 2014.

[19] A. Poungrat and T. Maneewarn, “A starfish inspired robot with multi-directional tube feet locomotion,” in *2017 IEEE International Conference on Robotics and Biomimetics (ROBIO)*. IEEE, 2017, pp. 712–717.

[20] M. S. Sngster and S. C. Brown, “Histology and ultrastructure of the tube foot epithelium in the phanerozonian starfish, astropecten,” *Tissue cell*, vol. 4, no. 3, pp. 503–518, 1972.

[21] S. Heydari, A. Johnson, O. Ellers, M. J. McHenry, and E. Kanso, “Sea star inspired crawling and bouncing,” *Journal of the Royal Society interface*, vol. 17, no. 162, pp. 20 190 700–20 190 700, 2020.

[22] X. Yang, R. Tan, H. Lu, and Y. Shen, “Corrections to ”starfish inspired milli soft robot with omnidirectional adaptive locomotion ability” [apr 21 3325-3332],” *IEEE robotics and automation letters*, vol. 6, no. 3, pp. 5348–5348, 2021.

[23] M. A. Bell, I. Pestovski, W. Scott, K. Kumar, M. K. Jawed, D. A. Paley, C. Majidi, J. C. Weaver, and R. J. Wood, “Echinoderm-inspired tube feet for robust robot locomotion and adhesion,” *IEEE robotics and automation letters*, vol. 3, no. 3, pp. 2222–2228, 2018.

[24] Y. Tian, N. Pesika, H. Zeng, K. Rosenberg, B. Zhao, P. McGuiggan, K. Autumn, and J. Israelachvili, “Adhesion and friction in gecko toe attachment and detachment,” *Proceedings of the National Academy of Sciences - PNAS*, vol. 103, no. 51, pp. 19 320–19 325, 2006.

[25] A. Cauligi, T. G. Chen, S. A. Suresh, M. Dille, R. G. Ruiz, A. M. Vargas, M. Pavone, and M. Cutkosky, “Design and development of a gecko-adhesive gripper for the astrobee free-flying robot,” 2020.

[26] S. Song and M. Sitti, “Soft grippers using micro-fibrillar adhesives for transfer printing,” *Advanced materials (Weinheim)*, vol. 26, no. 28, pp. 4901–4906, 2014.

[27] P. Glick, S. A. Suresh, D. Ruffatto, M. Cutkosky, M. T. Tolley, and A. Parness, “A soft robotic gripper with gecko-inspired adhesive,” *IEEE robotics and automation letters*, vol. 3, no. 2, pp. 903–910, 2018.

[28] C. Menon, M. Murphy, and M. Sitti, “Gecko inspired surface climbing robots,” in *2004 IEEE International Conference on Robotics and Biomimetics*. IEEE, 2004, pp. 431–436.

[29] B. Aksak, M. Murphy, and M. Sitti, “Gecko inspired micro-fibrillar adhesives for wall climbing robots on micro/nanoscale rough surfaces,” in *2008 IEEE International Conference on Robotics and Automation*. IEEE, 2008, pp. 3058–3063.

[30] K. Autumn and N. Gravish, “Gecko adhesion: evolutionary nanotechnology,” *Philosophical transactions of the Royal Society of London. Series A: Mathematical, physical, and engineering sciences*, vol. 366, no. 1870, pp. 1575–1590, 2008.

Appendix

Systems Design Phase		February										March															
Task	**Responsible**	19	20	21	22	23	24	25	26	27	28	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Presentation Preparation	All																										
Initial CAD model	Sampada																										
Presentation Practice	All																										
Proposal Presentation	All																										
Materials Purchasing	Raghav																										
Actuation system design	Peter - James																										
Electronic circuit design	Raghav																										
Control System design	James																										
Structure design	Peter																										
Gecko adhesive fabrication	Sampada																										
Underwater gecko testing	Sampada																										
Algorithm programming	Viraj																										
Detailed Design	Peter																										

Robot Construction Phase		March															April										
Task	**Responsible**	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5	6	7	8	9	10	11
Soft Structure Fabrication	Peter																										
Actuation testing	Viraj																										
Electronic circuit fabrication	Raghav																										
Gecko adhesive integration to structure	Sampada																										
Sensor data acquisition and processing	Viraj																										
Sensor integration	Raghav																										
Robot control programming	Viraj																										
Update 1 report review	All																										
PCB design	Raghav																										
Submit Project update 1	Viraj																										
PCB fabrication and mounting	Raghav																										
Actuation system integration	Peter																										

Robot Testing Phase		April																			May						
Task	**Responsible**	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7
Control System testing	James																										
Limb motion testing	Viraj																										
Sensor testing	James																										
Gecko adhesion testing on robot	Sampada																										
Update 2 report review	All																										
Robot motion testing	All																										
Project document writing	All																										
Video recording of robot motion	Peter																										
Submit Project update	Raghav																										
Video editing	Peter																										
Project document review	All																										
Video review	All																										
Submit Project Document	James																										
Submit Final project video	Peter																										