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Conceptualization and Topology Optimization of Ampheel: An Integration of Rolling Wheel and Turtle-Inspired Mechanism for Amphibious Mobile Robot

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ABSTRACT

The primary distinguishing feature of mobile robots is the ability to traverse various environments, setting them apart in the realm of robotics. The mobility of a robot hinges primarily on its locomotion mechanism, which dictates how it moves. The existing unimodal mobile robots are limited to work within the environment for which they are designed for and hence lack a scope to adapt the change in the terrain especially when they put to work in a mixed environment like land and water. Many applications like land and underwater search/rescue, shore infrastructure inspection, coastal area defence and security, offshore energy harvesting, space exploration, etc. demand a mobile robot that can traverse in both terrestrial and aquatic environments with the help of dual or multimodal locomotion mechanism, something like an amphibious animal. Most of the available amphibious robotic solutions have different appendages for both the environment, need human intervention to changeover the mechanism for transition, require different driving system for land and water locomotion and have fragile structures that limit the manoeuvrability. The proposed conceptual design called "Ampheel" is a novel amphibious locomotion mechanism inspired by the biomechanics of freshwater turtles. Ampheel incorporates a rigid wheel, enabling the robot to move on land, integrating soft actuators within it which emulate the turtle's leg-like extensions and enable the aquatic locomotion. Unlike the existing amphibious robots, the Ampheel utilizes the rotational motion of itself as a common driving system for both the environments. This reduces the need of multiple driving systems and also simplifies the control system. Ampheel is designed for safe travelling on land considering the maximum payload of robot as 20 kg including self-weight. Topology optimization of Ampheel is also carried out using ANSYS software for reduction of weight. Additionally, a unique interfacing shaft is designed that transmits the required torque to Ampheel for rotation and also channelise the compressed air to soft pneumatic actuators for inflation during rotation of Ampheel in aquatic setting. The fabricated Ampheel assembly is experimentally checked for failure under the applicable loading condition and found safe.

1. Introduction

Robotics is one of the fastest growing fields and has attracted many researchers to contribute. Robotics involves design, construction, operation, and use of the robots. The goal of robotics is to design machine that can help and assists humans in their day-to-day lives and keeps everyone safe. Research has been done and still continue in various advanced fields of robotics like Swarm Robotics, Bio Robotics, Soft robotics, Mobile Robotics etc.

Mobile robotics mainly deals with the robots which are capable to locomote from one place to another place for performing required task. The first choice of locomotion mechanism for a land based mobile robot is obviously tending to wheels due to the less complex structure, higher efficiency of manoeuvring on flat surface and ease of control. In spite of many such pros the use of wheel locomotion is limited to only flat and solid surfaces. The situation where wheels, the human invention, were not going to serve the purpose, researchers had taken inspiration from nature and tried to design the robot which has bio-inspired locomotion mechanism such as legs developed by Manolescu [1]. The other example is "BigDog" developed by Playter et al. [2] which is a four-legged robot resembles like a Dog. Rubio, Valero and Llopis-Albert [3] have presented an exhaustive review of various land based mobile robot equipped with different locomotion mechanism which is summarised and represented in Fig. 1. After having studied the land-based mobility the researchers explored the scope of robot mobility beyond the terrestrial environment to aerial [4] and aquatic settings. Russo and Ceccarelli [5] have provided the list of different locomotion mechanisms for terrestrial, aerial and aquatic setting which are reproduced in Fig. 2. Not being limited to single environmental locomotion, the researchers further extended the mobility scope of the robot to dual or multi environments, majorly nature inspired, and incorporate multimodal locomotion mechanisms as discussed by Adarsh et al [6]. The robots fitted with such multimodal locomotion mechanism that enables the robot to locomote on land as well as in air are classified as Aerial Hybrid robots for example "The flying monkey" developed by Mulgaonkar et al. [7] and robot developed by Bachmann et al. [8] which can run and fly.

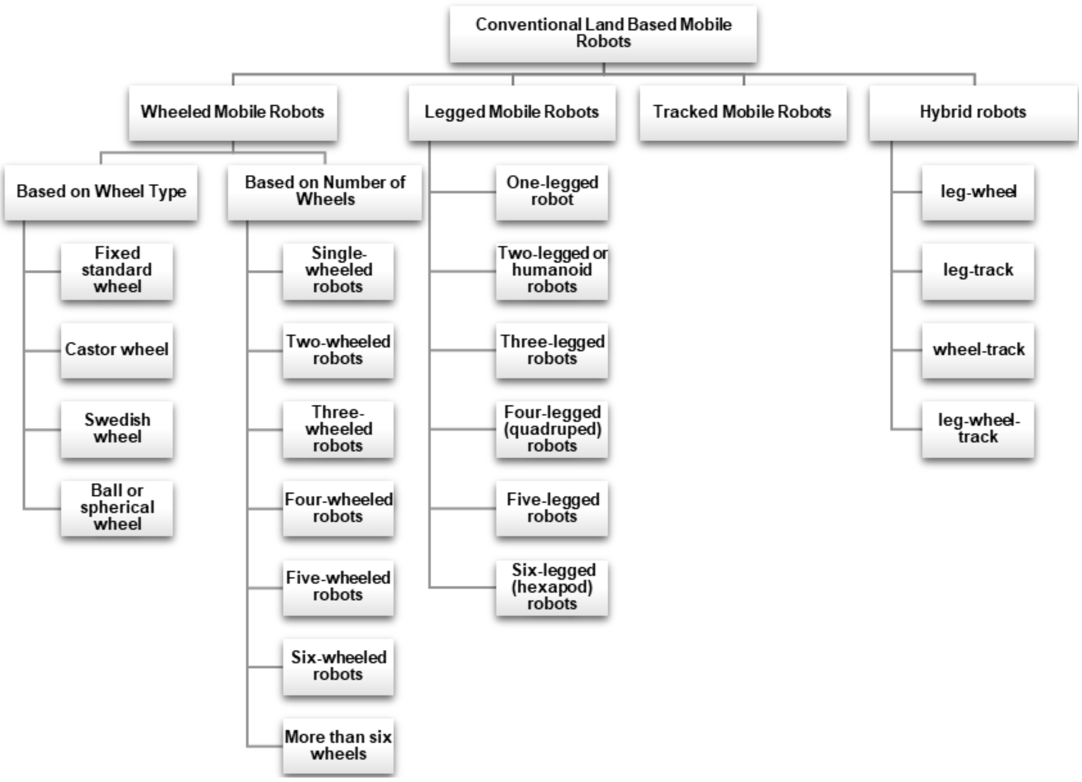


Fig. 1. Conventional land based mobile robots [3]

The multimodal robot that can move on land as well as can also manoeuvre in aquatic environment are called Amphibious robot. Many such robots are developed by researchers and put in practice for various applications such as underwater railway inspection and maintenance robot developed by Liu et al. [9], visual inspection robot for strainer assembly of water tank in a nuclear power plant proposed by Jang et al. [10], spherical rolling robot by Diouf et al. [11], Mudskipper-inspired amphibious robotic fish by Lin et al. [12], robot with self-rotating paddle-wheel mechanism proposed by Kim et al. [13], tortoise-like soft mobile robot from Sun et al. [14], Crab-like robot proposed by Hu et al. [15], amphibious vehicle for coastal surface zone survey as proposed by Bak et al. [16], etc. These robots are found useful in the applications like environmental monitoring, land and underwater search/rescue, marine ecosystem study, shore infrastructure inspection, coastal area defence and security, underwater archaeology, offshore energy harvesting, space exploration, etc. A few more examples of bio-inspired amphibious robots are discussed in the following section.

An autonomous amphibious robot AQUA developed by Dudek et al. [17] gathered so much attraction among the researchers due to its characteristic to swim via motion of its legs rather than using conventional thrusters. AQUA is based on RHex (proposed by Altendorfer et al. [18] and Saranli et al. [19]), a terrestrial six- legged robot designed inspired from cockroach locomotion. AQUA is a biologically inspired robot, capable to operate both legged walking and swimming. It was built for the industrial aquatic task mainly concentrating on Site Acquisition and Scene Reinspection (SASR). However, it needs human intervention to changeover the mechanism to transit from land to water and vice-versa.

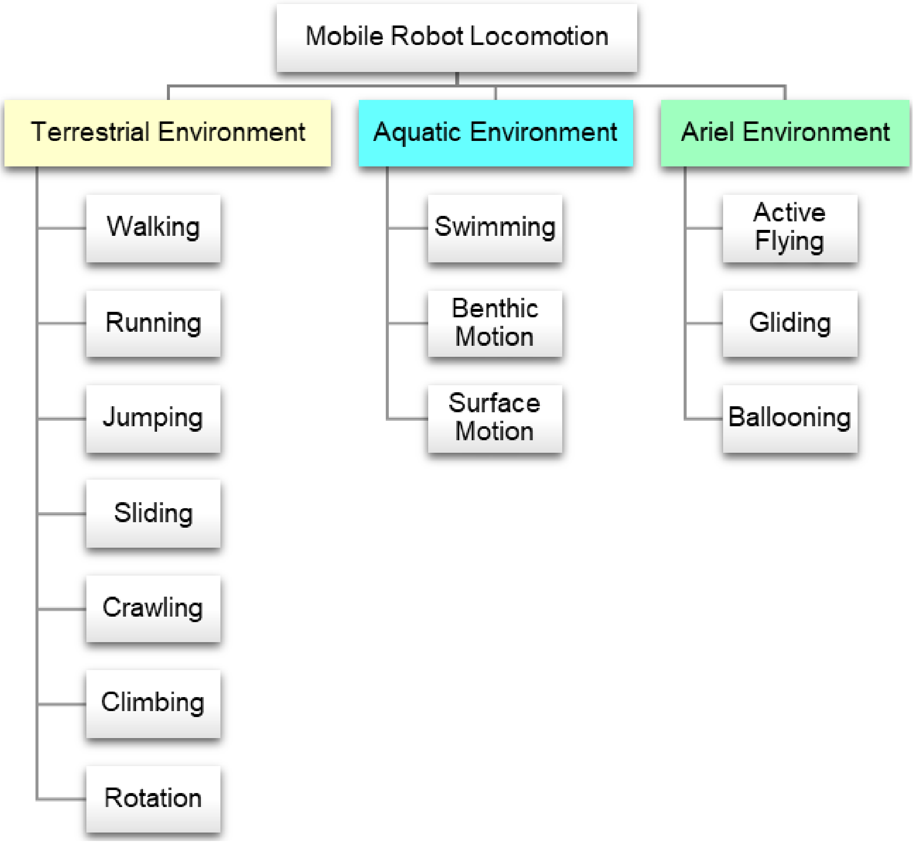


Fig. 2. Mobile robot locomotion [5]

The multi environmental mobility is much useful for space exploration for example Amphibious Rover for a mission to Titan [20] wherein the propulsion was obtained by raising the wheels, above the liquid and using them as paddle-wheels. Yang et al. [21] had designed the AmphiRobot which has modular design such that the robot can do fish-like swimming in horizontal plane and dolphin-like swimming in vertical plane but this needs manual changeover of mechanism. Later it was upgraded to AmphiRobot II [22], [23] in which interchangeable propeller design was replaced by a novel wheel-propeller-fin mechanism that incorporates wheel and fin both to avoid the interchangeability. However, this lacks to provide high torque requirement. Liang et al. [29] presented the concept of AmphiHex-I by taking inspiration from AQUA and RHex in which transformable leg-flipper composite propulsion mechanism is used. The concept of AmphiHex-I is based on transformable leg-flipper module. Further development was done in AmphiHex-1 considering design by Zhang et al. [30] and considering gait planning and gait transition by Kong et al. [31]. An attempt was made in AmphiHex-I to overcome the limitation of AQUA (i.e. manual interchangeability) by using transformable leg-flipper module. This is a single module which can work as leg and flipper both without any manual interchange but this reduces the robot stiffness due to frail structure. Outdoor locomotion experiments were conducted on various substrates to validate the effectiveness of AmphiHex-I's transformable flipper legs and locomotory performance by Zhang et al. [32]. Later on, it was observed that the novelty of the AmphiHex-I (i.e. transformable leg-flipper module) became its limitation. In the discussed module, a leg is generated by combining small-small segments by which the leg-fin transformation is possible. This approach makes the structure fragile and increases the probability of damage to the structure. Another issue was in bending of the legs. Bending is possible in only one direction, so when the leg counter rotates in the opposite direction from its original walking mode, the leg behaves like a straight rod and generates great impact, which is absolutely inefficient for locomotion. To avoid this issue, a new version "AmphiHex-II" was proposed by Zhong et al. [33] with a novel design of variable stiffness leg with carbon fiber frame which is strong enough to serve the purpose. Experimental results of the AmphiHex-II shows that maximum speed was achieved by the robot is about 0.35 m/s which can be improved further by detail investigation and research.

The kinematic models of a reconfigurable robot employing e-Paddle (Eccentric Paddle [24]) mechanism called ePaddle-based quadruped robot (eQuad) were developed by Sun and Ma [25]. It suggests that this unique reconfigurable ePaddle mechanism has the potential to achieve both legged and wheeled locomotion through five principal kinds of gaits as discussed by Sun et al.[26] which are wheel-like rolling, legged walking [27], wheel-leg-integrated rolling, and two aquatic paddling gaits [28]. Kim et al. [34] had developed a prototype of robotic platform inspired from the basilisk lizard, which is well known for its ability to run on water surface. At initial stage, the issue was in selection of the shape of footpad which was solved by experimental trials and at the end, rectangular shape was selected for better terrestrial and aquatic locomotion. However, independent motion of each leg is not possible to improve the manoeuvrability. Another example of amphibious robot is "R-crank" presented by Yamada et al. [35] which uses the improved locomotion mechanism of "Crank-wheel" robot developed by Nakano and Hirose [36].

The available amphibious robots have one or other kind of limitations like different driving system for both the environment, manual intervention for interchanging mechanism, fragile structure, less degree of manoeuvrability, etc which attract the scope of the further research and development in this field. An attempt is made to conceptualize and design a novel amphibious locomotion mechanism that utilizes a common driving system for both the environments, doesn't need human intervention for interchanging the mechanism while transiting from land to aquatic environment or vice-versa and also has sufficient rigidity with good degree of manoeuvrability. The objective of the present work is to design amphibious locomotion mechanism that provides a wheel-based locomotion for terrestrial environment and roving or paddling type of locomotion using axially inflated soft pneumatic actuators (SPA) in aquatic environment, utilizing a common driving system (i.e., rotation) for both the environments. The proposed wheel is also needed to have housing and other support system for soft pneumatic actuators to rove over the water surface by the wheel rotation motion. Additionally, a novel way to channelise the inflating air supply to soft actuator during rotation of the wheel is also required to be thought off. The research contribution of the proposed design of Ampheel is to advance the capabilities of mobile robots in traversing diverse environments and widen the scope of further research in multimodal locomotion mechanism for mobile robots.

Having identified research gap and the objective of the present work in Section 1, Section 2 discusses about the bio-inspired conceptualization of Ampheel, fabrication of Ampheel and design of interfacing shaft. The topology optimization, FEA of interfacing shaft and the experimental investigation of Ampheel assembly is deliberated in Section 3. The conclusions, observations and future scope are noted in Section 4 with listed references at the end.

2. Methods

Wheels are the most effective locomotion mechanism for flat, continuous and solid surfaces as it offers many advantages like ease of control, simplicity of design and construction. It is best suited on ground locomotion as it can provide good amount of tractive effort i.e. the amount of force between wheel and track to locomote the body by overcoming the effect of friction resistance and rolling resistance.

2.1. Bio-Inspired Conceptualization

Wheels struggle to provide the required force when it loses the continuous contact of solid surface as in case of aquatic environment. To manoeuvre in aquatic setting, many mechanisms exist in nature adapted by various aquatic animals [37]-[42] as depicted in Fig. 3. It is observed that the animals like Fish, Salamander, Crocodile, Snake etc. are using undulation of their body parts for their underwater manoeuvring which can be replicated by multiple connected structural links motion with multi degree of freedom. These types of hyper redundant structures are not only complex in construction but also need multiple actuators for each independent motion of links. In addition, it is also difficult to design an adjoining mechanism with this undulating bodies for land locomotion and hence it is not found suitable for the proposed work. The animals like Jellyfish and Octopus have very soft body and uses their tentacles to generate the trust force for the motion in the water. This mechanism is also not considered for present work as it lacks a rigidity required for land locomotion. Frog uses a kicking action of its rear limbs to generate the thrust force for underwater mobility while jumping action on land. The jumping gait using legs has its own limitations and complexity in operations on land and hence the frog locomotion is also disregarded in the proposed design.

The anatomy of the turtle body and its locomotion pattern over land and underwater finds it the suitable candidate to consider as biological inspiration for the proposed work. The turtles are broadly categorized in three types, (i) sea water turtle, (ii) fresh water turtle and (iii) terrestrial turtle (tortoise). Unlike sea water turtle and fresh water turtle the terrestrial turtles, also called tortoise, can majorly live on land and not a good swimmer. Sea water turtle uses flapping action (Fig. 4 (a)) of their large, strong and muscular forelimbs to swim in ocean [43]. Their hindlimbs are very small and not have enough propulsive functionality. Sea water turtle cannot lift their body using their limbs and hence has limitation in terrestrial locomotion. The fresh water turtle has rigid and robust shell encompasses its body. It has four active limbs equally strong enough to contribute in mobility. Fresh water turtle can swim in ponds, lakes, flowing rivers by rowing action of all four limbs (Fig. 4 (b)). The anatomy of the fresh water turtle body as well as its dual locomotion mechanism is considered as a biological inspiration for the proposed design for aquatic locomotion. Fresh water turtle's ability of retracting the limbs inside the body is also considered in the proposed design for reconfiguration of locomotion mechanism from land to water transition.

An attempt is made here to design a locomotion mechanism such that it utilizes the wheel rolling action for land locomotion and also replicate the rowing action of fresh water turtle's leg for aquatic environment using limb like component. The wheel provides circular motion while rolling on the land. The same circular motion of the wheel is to be utilized to move the limb like structure in the aquatic domain so that no separate actuation and mechanism is needed for both the domain and reconfiguration will be flow less during transit. For this, it is required that the circular motion of the limb like structure must compensate the rowing motion profile of turtle's leg.

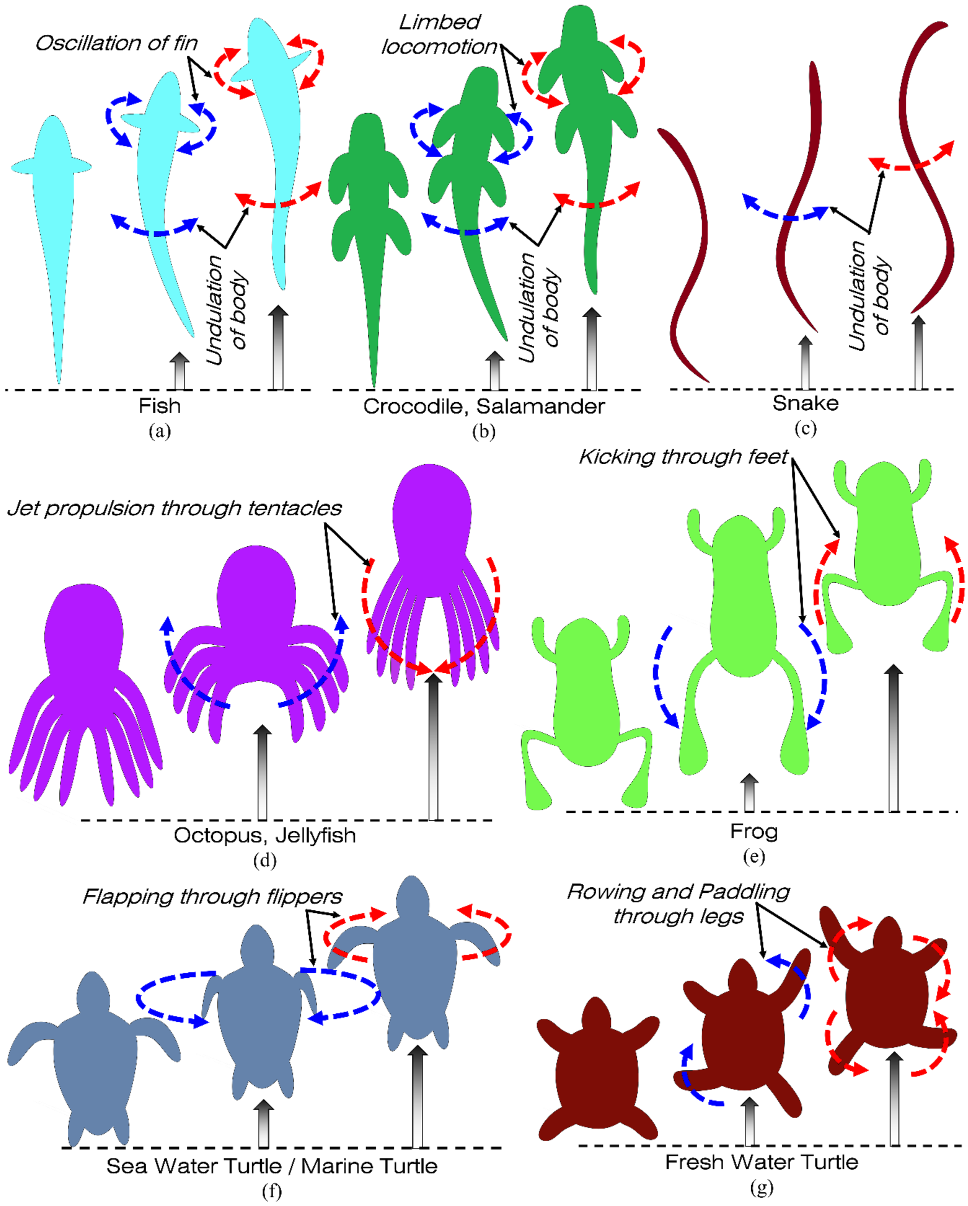


Fig. 3. Aquatic locomotion of animals

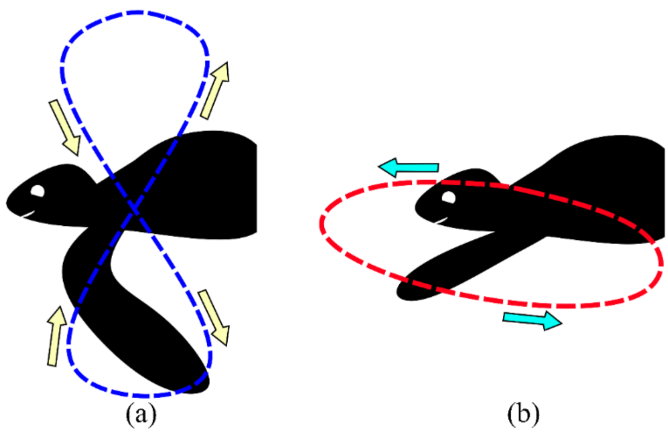


Fig. 4. Trajectory of (a) sea water turtle and (b) fresh water turtle [43]

The motion of the fresh water turtle leg forms an elliptical cone. Proximate trajectory, the approximate locus that involves close proximity with path traced by the tip of the leg of fresh water turtle, is shown in Fig. 5. Here the elliptical arc 'A-B-C' represent the propulsive stroke while the arc 'C-D-A' shows recovery stroke. The major cone angle (ψ) shows the total angular travel of leg in horizontal plane that decides the major axis of the ellipse while the minor cone angle (ζ) shows the total angular travel of leg in vertical plane which decides the minor axis of the ellipse. Using the value of the major and minor axis of the ellipse, the total length of stroke can be estimated by considering the Ramanujan's approximation theorem [44]-[48] for circumference of an ellipse (P_e) as per (1) and (2).

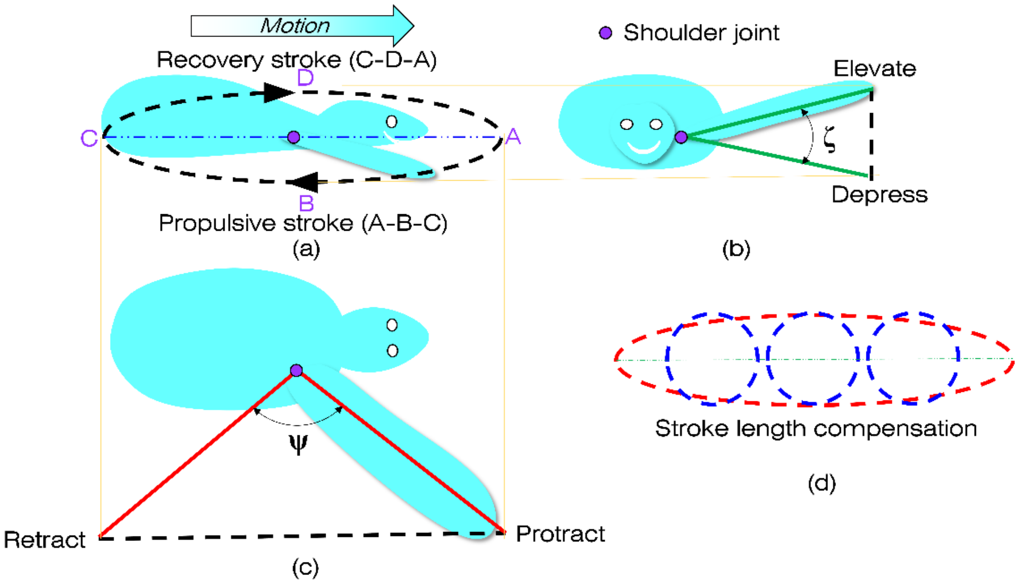


Fig. 5. Proximate trajectory of fresh water turtle legs with proposed compensation

$$P_e \approx \pi(a+b)\left(1+\frac{3\left(\frac{(a-b)}{(a+b)}\right)^2}{10+\sqrt{\left(4-3\left(\frac{(a-b)}{(a+b)}\right)^2\right)}}\right) \tag{1}$$

Where, a is semi major axis ≈ L sin (ψ/2) and b is semi minor axis ≈ L sin (ζ /2), while L = length of leg. Substituting these values in (1),

$$P_e \approx \pi\left(\left(L\sin\left(\frac{\psi}{2}\right)\right)+\left(L\sin\left(\frac{\zeta}{2}\right)\right)\right)\left(1+\frac{3\left(\frac{\left(\left(L\sin\left(\frac{\psi}{2}\right)\right)-\left(L\sin\left(\frac{\zeta}{2}\right)\right)\right)}{\left(\left(L\sin\left(\frac{\psi}{2}\right)\right)+\left(L\sin\left(\frac{\zeta}{2}\right)\right)\right)}\right)^2}{10+\sqrt{\left(4-3\left(\frac{\left(\left(L\sin\left(\frac{\psi}{2}\right)\right)-\left(L\sin\left(\frac{\zeta}{2}\right)\right)\right)}{\left(\left(L\sin\left(\frac{\psi}{2}\right)\right)+\left(L\sin\left(\frac{\zeta}{2}\right)\right)\right)}\right)^2\right)}}\right) \tag{2}$$

Considering $\psi \approx 100^0$ and $\zeta \approx 25^0$ (from the literature [49]) in (2), $P_e \approx L \times 3.333$ unit. P_e shows the length of elliptical path traced by the turtle's leg tip during the stroke. The proposed mechanism is designed such that it should compensate the same stroke length by the circular motion of some limb like structure called as bio-inspired leg henceforth. Considering the semi minor axis ($b \approx L \sin(\zeta/2) \approx L \times 0.216$) as the radius of the circular motion of the proposed leg, the length of the path traced by it is $P_c \approx L \times 1.359$ unit which is almost 2.45 times less than the required stroke length i.e., P_e (=$L \times 3.333$ unit). To compensate the total stroke length (P_e), multiple of similar legs are needed. In the proposed design, 3 bio-inspired legs are used which compensate the elliptical motion of the turtle leg as shown in Fig. 5 (d) and integrated with the rolling wheel.

Fig. 6 shows the first conceptual design of an amphibious wheel (Ampheel) which is a rigid wheel structure with three equally spaced cavities to house the bio-inspired leg. These legs remain in the cavity while the rolling action of the wheel is being utilized for land locomotion as if like the turtle's leg retracted in its shell. In the aquatic setting, these legs protrude out from the wheel body and mimic the rowing action of turtle's leg upon the rotation of the Ampheel. To mimic the retraction and stretching movement of turtle's leg as well as to provide the sufficient propelling effect, the bio-inspired legs are specially designed in the form of axially expanding SPA as in [50]. The SPAs are made of soft elastomer materials moulded in a design to have multiple cavities within and expand when inflated using air pressure. These SPAs are the best suitable in the proposed design of bio-inspired legs. The length of SPA is decided as 60 mm considering the average length of the turtle's leg as cited in the literatures [51], [52].

To accommodate this SPA of 60 mm length in the wheel body before extension, the cavity of the same depth is needed. Three cavities are provided at triangularly spaced at equal radius on the Ampheel. The cavity is created at the minor angle ζ to replicate the rowing motion of turtle leg when extended. The cavity depth (60 mm) and inclination (ζ) further fix the Ampheel width as 85 mm and the diameter as 200 mm to a minimum requirement as shown in Fig. 6.

Conceptual functionality of the Ampheel is presented in Fig. 7 considering the locomotion for terrestrial environment (Fig. 7(a)) and aquatic environment (Fig. 7(b)). The rigid robot body is fitted with four Ampheels making it a four wheeled drive robot. When the robot is in terrestrial environment, it can locomote by rotation of wheel and SPAs remain inside during the terrestrial locomotion. Aquatic environment can be handled by inflated SPAs, which protrude out from wheel body upon inflation and help the robot to propel in the aquatic environment by mimicking the rowing motion.

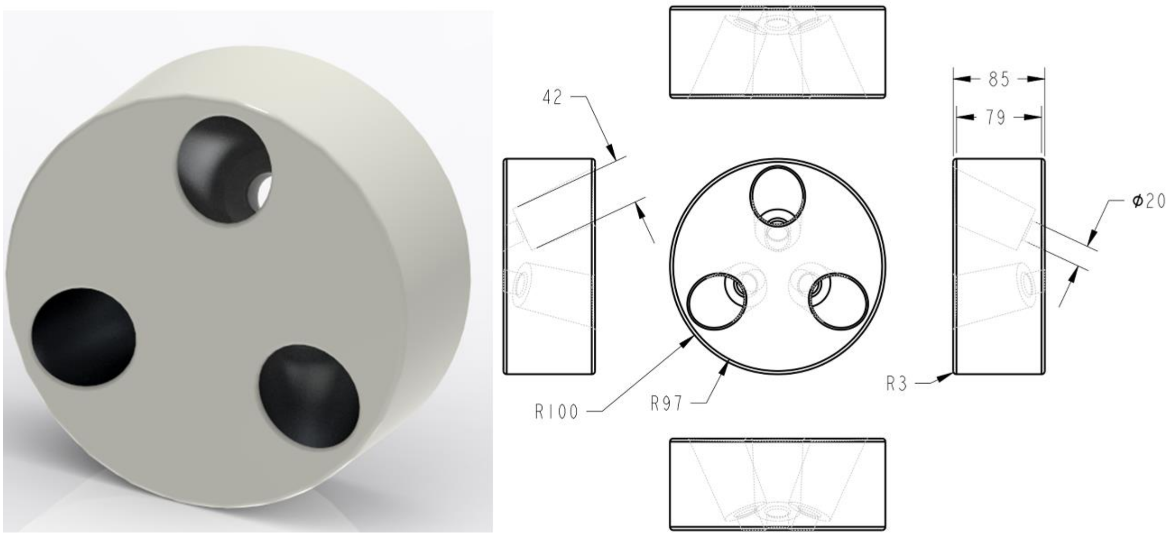
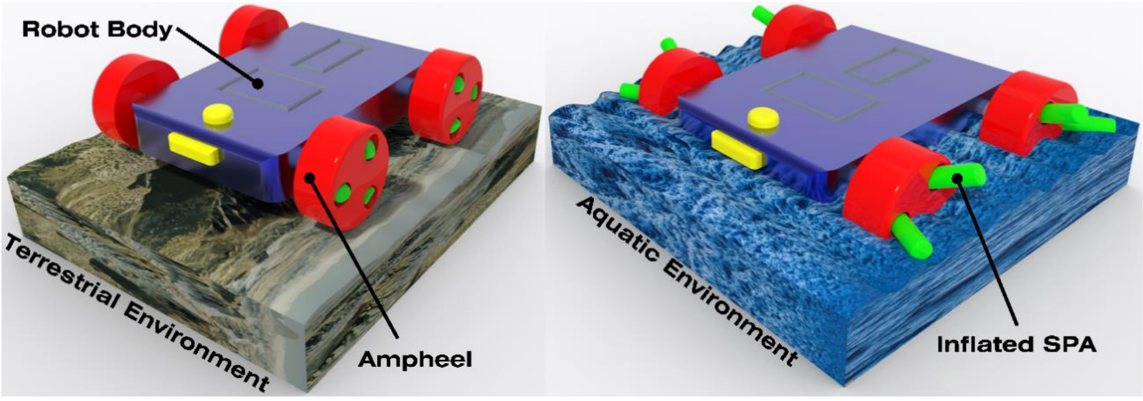


Fig. 6. First version of ampheel

2.2. Fabrication of Ampheel

Considering the dual environments functionality, the material selection to fabricate the Ampheel become crucial. The Ampheel material should be non-corrosive, having good strength, light weight but tough and durable, having good impact strength and wear resistance in addition to good heat resistance. The conventional metals are not suitable for the present application due to the corrosive property and hence polymer is the more appropriate option. Looking to the intricate shape of Ampheel the conventional plastic moulding is difficult. Hence, 3D printing approach over traditional manufacturing is used to fabricate the Ampheel considering design freedom and the ability to create complex designs. Two most popular materials for 3D printing are PLA (polylactic acid) and ABS (acrylonitrile butadiene styrene).



(a) (b)

Fig. 7. Locomotion in (a) terrestrial environment (b) aquatic environment

PLA is the easiest material for printing but at the same time it is brittle and less resistant to heat and chemicals. These characteristics of PLA limits its application on actual field. On the other end, ABS fulfils the required characteristics and making itself a suitable candidate for functional prototype. Fig. 8 shows the first model of Ampheel, fabricated using Fusion Deposition Method (FDM) 3D printing technology from ABS material. Here Creality Ender 3 Max 3D printer is used with Creality Slicer 4.8.2 software wherein layer height is kept 0.2 mm, infill density is of 20% with triangular pattern is incorporated. ABS material has very high probability of warping, cracking and poor adhesion especially when open frame 3D printer is used. These issues can be minimized with application of sufficient amount of adhesion on bed and by adjusting specific settings in 3D printing process. These settings include printing speed (30 mm/s), retraction speed (25 mm/sec), build plate adhesion type (raft), draft shield (Activate).

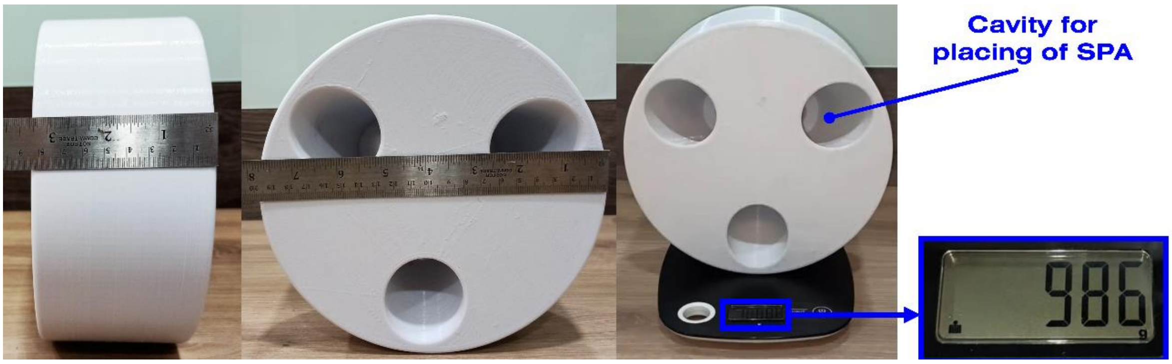


Fig. 8. Fabricated ampheel

2.3. Design of Interfacing Shaft

To demonstrate the intricate assembly elements of any symmetric vehicle a quarter vehicle model is commonly used. Here the proposed Ampheel is to be fitted with the mobile robot symmetrically and hence Quarter Mobile Robot Model (QMRM) is used to show case the assembly of Ampheel with other components. Conceptual design of QMRM is shown in Fig. 9 with other components such as

DC geared motor, gear, control unit, interfacing shaft and robot body. A DC geared motor provide the necessary torque which is transmitted to Ampheel through a gear drive and an interfacing shaft.

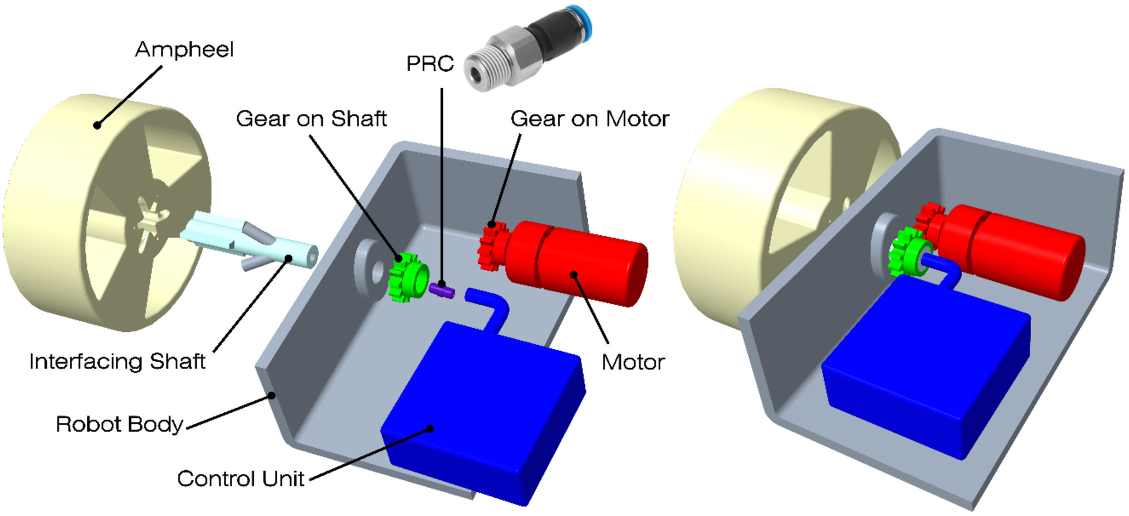


Fig. 9. Conceptual design of quarter mobile robot model (QMRM) (a) exploded view (b) assembled view

As mentioned earlier the Ampheel houses SPA which will be inflated by air pressure. The constant air pressure is required to be maintained until the SPAs are in use with the rotation of the Ampheel and for the same the SPAs are required to be connected with the air pressure source continuously. It is a challenge to maintain the SPAs connection with air supply while Ampheel is rotating without entangling of pneumatic tubing. This challenge is overcome by using a Pneumatic Rotary Connector (PRC) (as shown in Fig. 9) with specially designed interfacing shaft. The interfacing shaft serves dual role of transmitting power to Ampheel for rotation as well as to channelise the air flow to SPAs. The design of interfacing shaft is shown in Fig. 10. The interfacing shaft has three external splines on its one end that fix into the corresponding slots in Ampheel such that power transmission takes place effectively without slipping. Employing three splines offers a robust and reliable method of connecting a shaft with a rolling wheel, providing balanced load distribution, stability, and enhanced reliability. The other end of the shaft is hollow and has three hollow cylindrical protrusions which are connected with the three SPAs housed in the cavities of Ampheel through pneumatic tubing. The hollow shaft end is connected to the control unit through PRC.

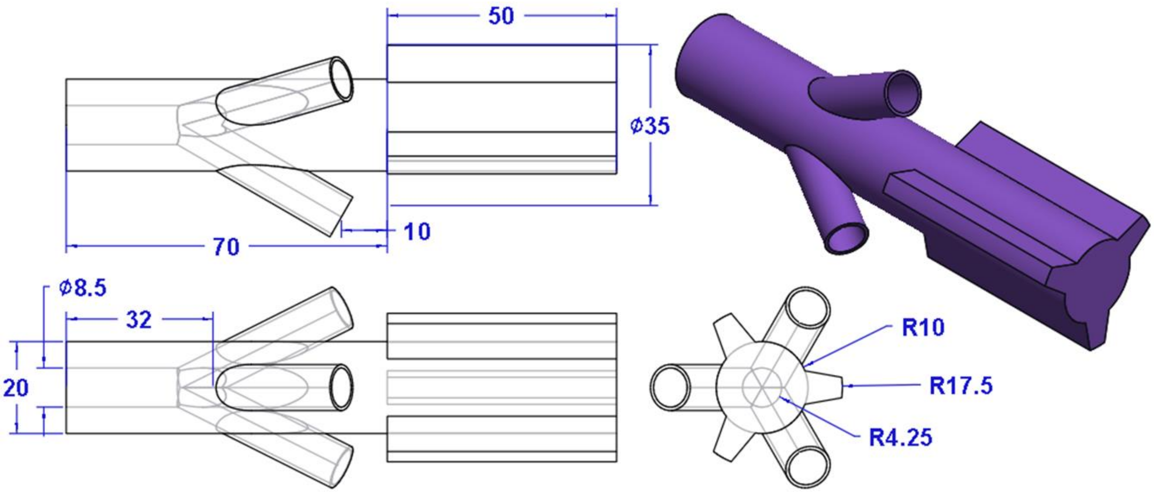


Fig. 10. Design of interfacing shaft

3. Results and Discussion

3.1. Topology Optimization

The first version of Ampheel as shown in Fig. 8 weighs 986 gm which leads to around 4 kg for four Ampheels attached to the robot body. This increases the self-weight of the robot which further limits the payload capacity of the robot. It is thereby needed to minimize the weight of Ampheel without compromising the strength. This is achieved by topology optimization of Ampheel. Topology optimization is carried out using ANSYS simulation software which suggests the places from where the materials can be removed without significant effect on the strength. The step-by-step procedure of topology optimization using ANSYS is shown in Fig. 11. The main criteria of optimization here is to reduce the mass keeping the strength in the permissible limit.

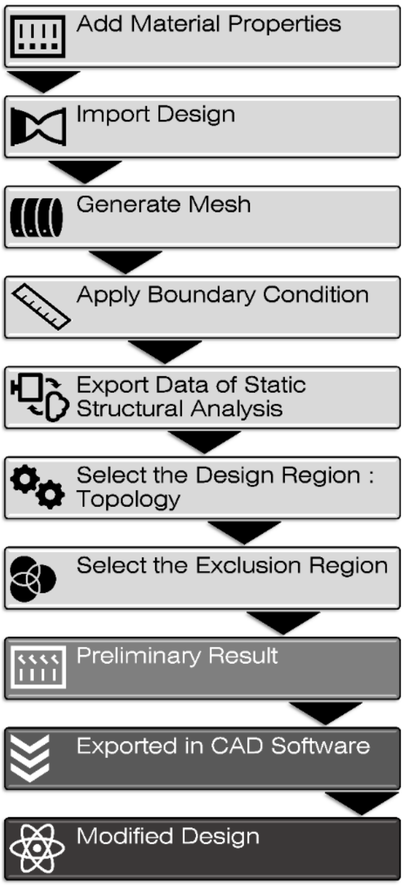


Fig. 11. Approach of topology optimization

Here the total weight supported by four Ampheels is assumed as 200 N including robot body weight and the payload. As per the design, four Ampheels are attached symmetrically on either side of the robot body and hence each Ampheel withstand the load of 50 N. The Ampheel has three equi-spaced cavities in it due to which the load bearing area differs at different locations as shown in Fig. 12. In case 1 (in Fig. 12) the load bearing area (LBA) is maximum while it is minimum in case 2 when one of the cavities is at the bottom most location. For both the cases the static structural analysis is carried using ANSYS software. It is observed that the maximum stress produced is 0.15932 MPa and 0.18878 MPa respectively for case 1 and case 2 (refer Fig. 13 and Fig. 14). The tensile strength of the ABS material is 26.84 MPa (as shown in Table 1) which is far greater than the induced stress. This shows that the present version of Ampheel is much overdesigned and has ample scope of optimization to reduce the material and weight keeping the stress in the permissible limit under the action of same payload of 50 N.

It is previously mentioned that the diameter and width of the Ampheel cannot be reduced considering the housing of SPAs and hence a topology optimization is carried out using ANSYS software. Excluding the diameter, width and housing of SPAs, the remaining areas of the Ampheel are considered for removal of materials based on minimum stress. Preliminary results of topology optimization obtained from ANSYS are presented in Fig. 15. Results show the possible domain from where the material can be removed. Considering the suggestion of ANSYS software a revised version of Ampheel is designed as shown in Fig. 16.

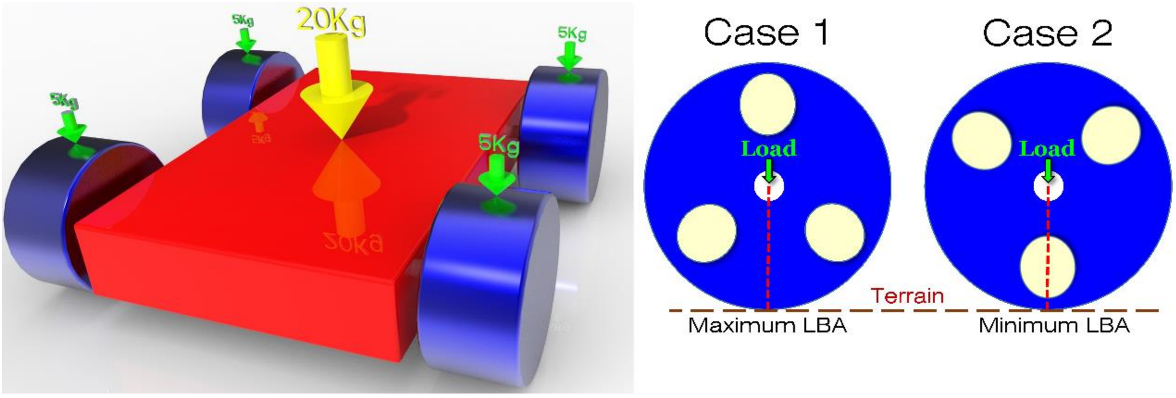


Fig. 12. Boundary conditions for finite element analysis

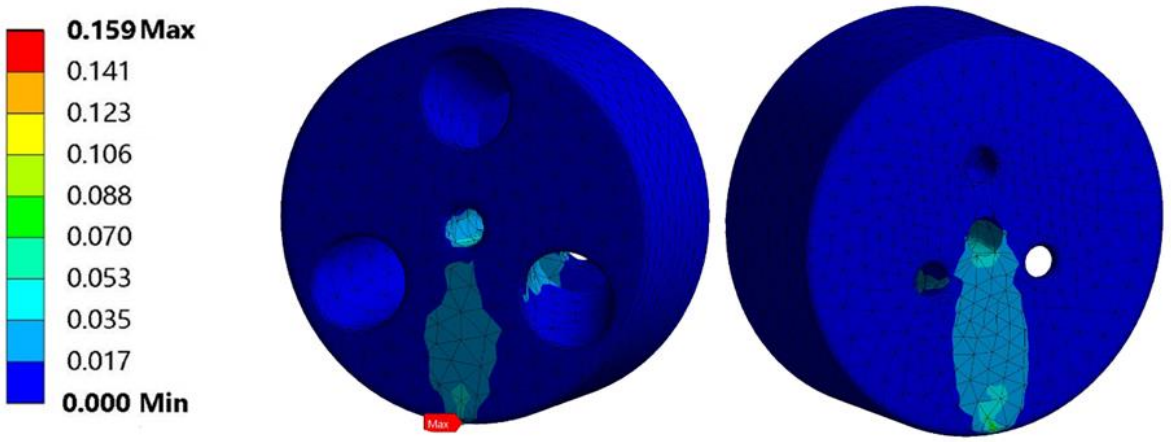


Fig. 13. Front and back isometric views for case 1 under 50 N applied load

Table 1. Material properties considered for finite element analysis [53], [54]

Material	Tensile Strength	Density	Young's Modulus	Poisson's Ratio
Acrylonitrile Butadiene Styrene (ABS)	26.84 MPa	1.04 gm/cm^3	2400 MPa	0.37

The optimized Ampheel is fabricated which weighs 348 gm (as shown in Fig. 16) which is 64.7% less than the previous version. The static structural analysis of revised version of Ampheel is also carried out using ANSYS and results are produced in Fig. 17 and Fig. 18 for both the cases under the application of 50 N payload. The maximum stress produced in both the cases is 0.720 MPa and 0.315 MPa which is still in safe permissible limit. This shows that the optimization of Ampheel doesn't compromise the overall payload capacity of robot rather increase it due to reduction in weight of Ampheel. The optimized Ampheel also maintain the structural integrity of the initial design to accommodate the SPAs and to provide sufficient rolling contact for terrestrial environment. Due to reduction in weight, less material is needed for manufacturing using 3D printing and it also saves time and energy. The further optimization can still be applied by reducing the Ampheel rim thickness but considering the ease of fabrication, possibility of impact loading and other unforeseen circumstances, the present design of Ampheel is considered as optimized design.

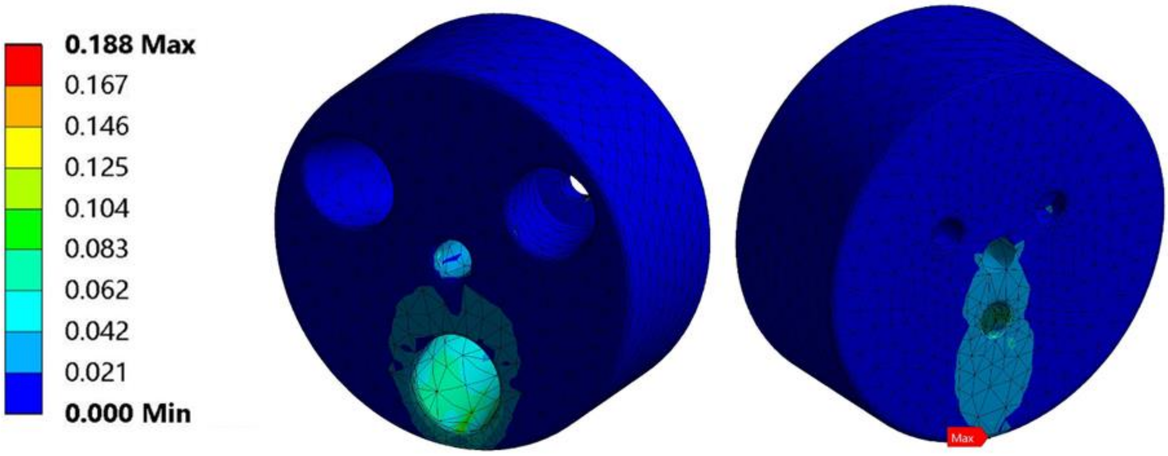


Fig. 14. Front and back isometric views for case 2 under 50 N applied load

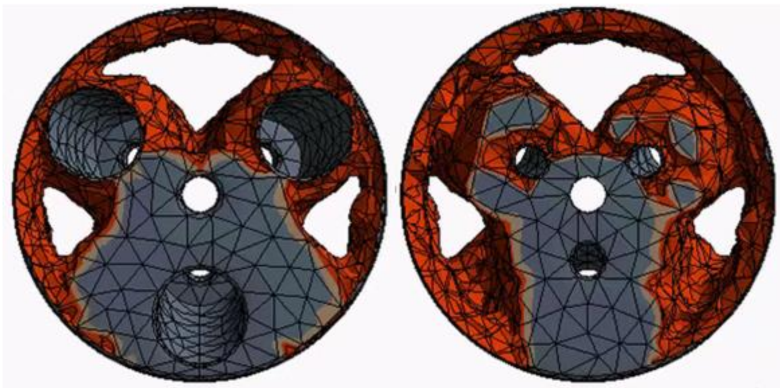
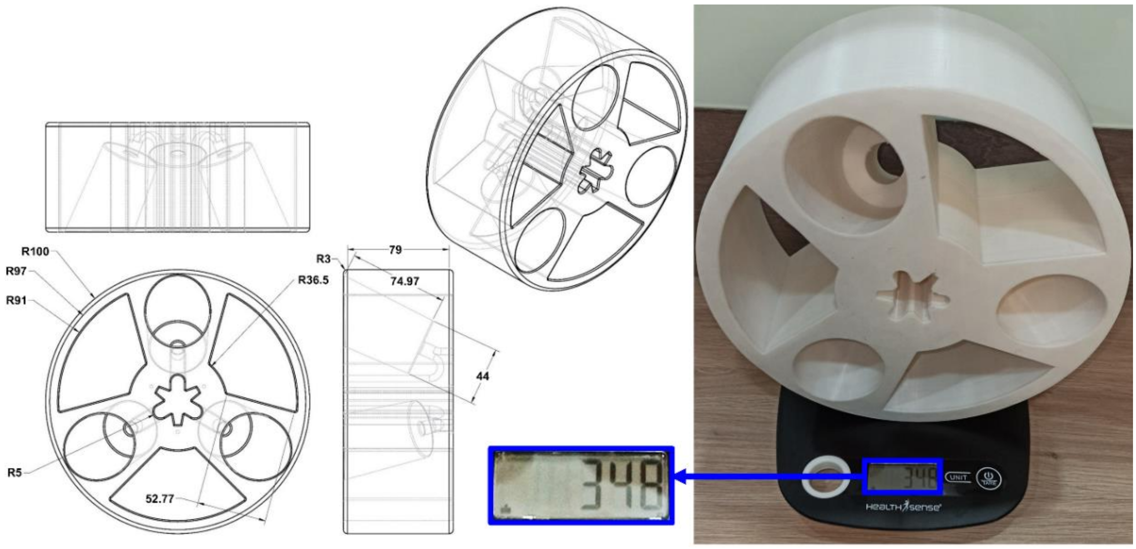


Fig. 15. Preliminary results of topology optimization



(a) (b)

Fig. 16. Optimized ampheel (a) orthographic and isometric views (b) actual image

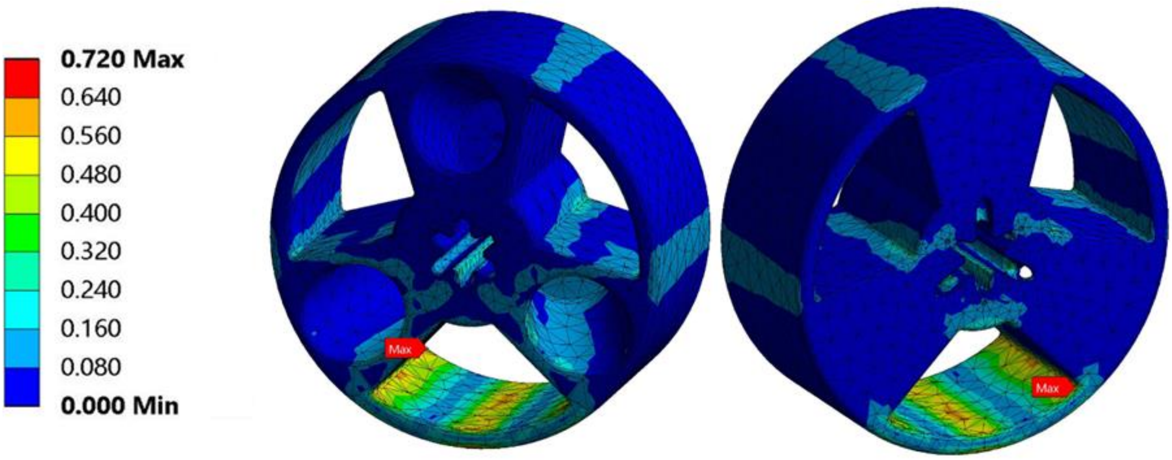


Fig. 17. Front and back isometric views for case 1 (optimized ampheel) under 50 N applied load

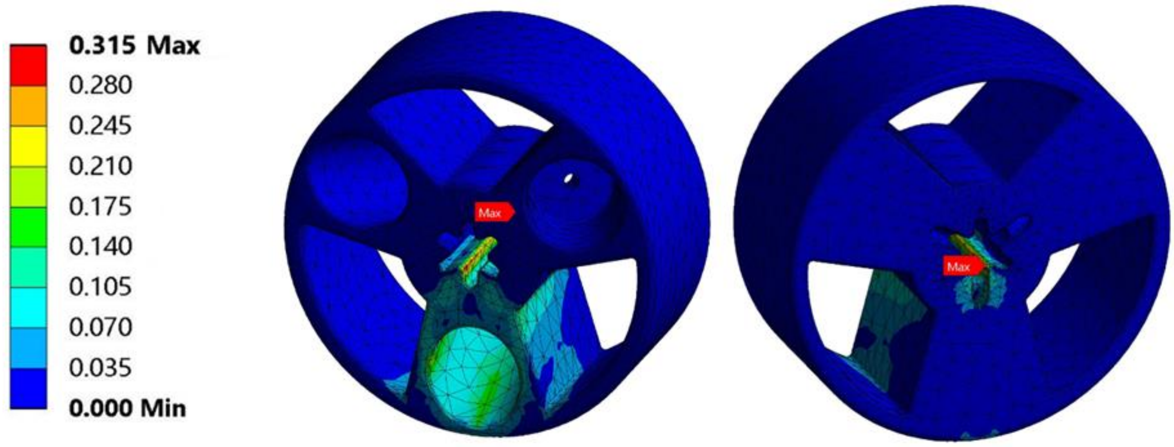


Fig. 18. Front and back isometric views for case 1 (optimized ampheel) under 50 N applied load

3.2. FEA of Interfacing Shaft

The interfacing shaft is a critical component that transmit the power from motor to Ampheel and bear the maximum load. The stress analysis (Fig. 19) of interfacing shaft is carried out using FEA to check the strength. The static structural analysis of the shaft is carried out in ANSYS workbench wherein the hollow end of the shaft is considered fixed while the other end is attached to the Ampheel. The tractive effort acting on the wheel is estimated as,

$$F_t \approx (\mu_f + C_{rr})W_1 \tag{3}$$

Where, μ_f is Coefficient of friction = 0.2 to 0.6 [55]-[58], C_{rr} is Coefficient of rolling resistance = 0.01 to 0.35 [55]-[58] , W_1 is load acting on single wheel = 50 N (from Fig. 12). Here, μf + Crr = 1 is considered for extreme condition which gives Ft ≈ 50 N. As shown in Fig. 19 (a), the Ampheel is loaded with total tractive effort of 50 N acting tangentially over the cylindrical surface while the free end of the interfacing shaft is provided with fixed support. The stress distribution in wheel-shaft assembly is shown in Fig. 19 (b). The high stress concentration is observed at the point of intersection of shaft main body with the cylindrical protrusions as shown in Fig. 19 (c). The maximum von-Mises stress of 18.42 MPa is observed which is under the permissible limit with factor of safety of 1.46 considering material properties listed in Table 1.

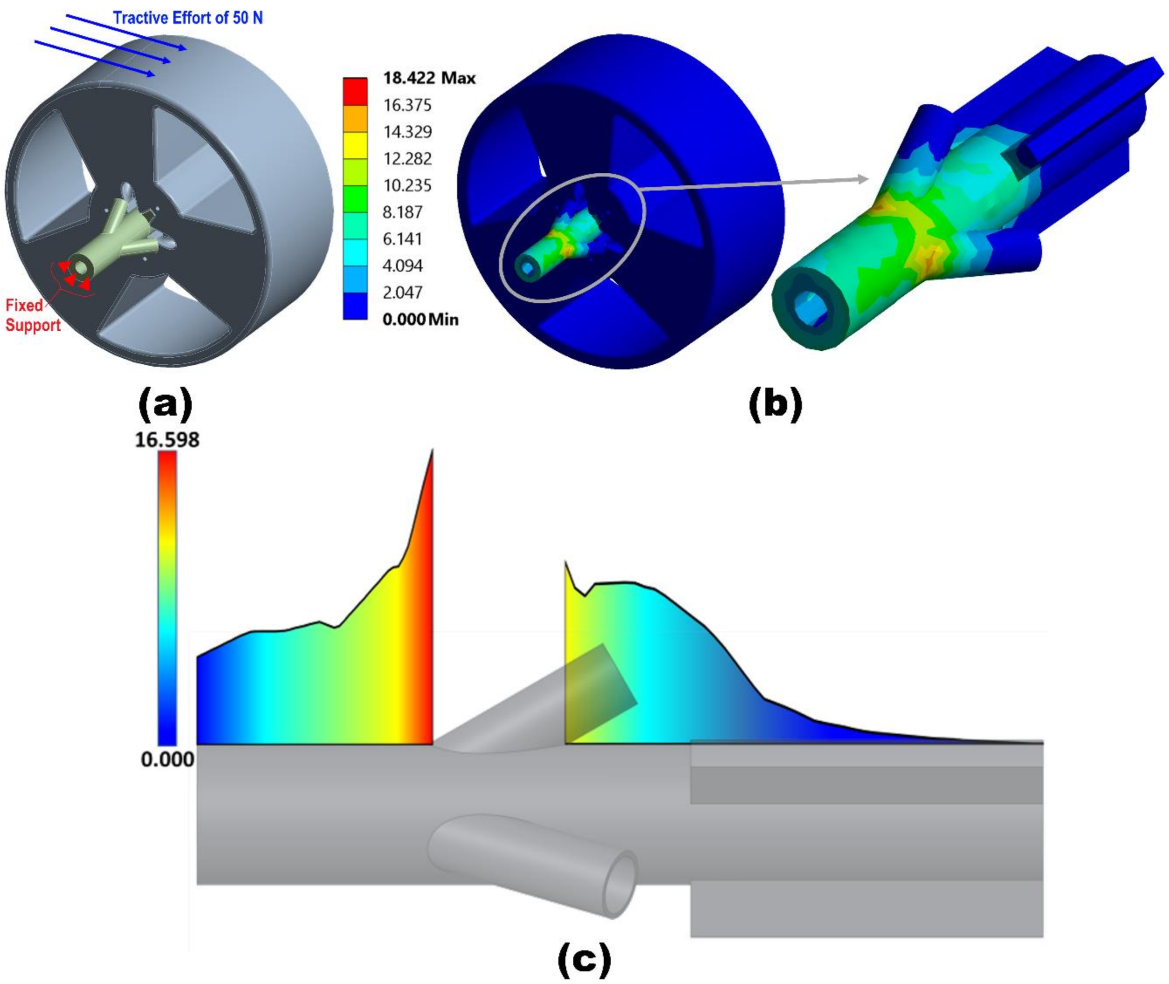


Fig. 19. FEA simulation using ANSYS (a) boundary conditions, (b) von-mises stress distribution for wheel-shaft assembly, (c) linearised von-mises stress distribution over the longitudinal section of the shaft

3.3. Experimental Investigation

The Ampheel with interfacing shaft is fabricated, assembled and tested for bending and torsion by the application of design load of 50 N (~5 kg) in radial and tangential direction respectively. Fig. 20 shows the experimental set up consists of UR10e six axis robotic manipulator, digital spring gauge, inelastic string, spirit level indicator, Ampheel assembly and a fixed support. The interfacing shaft of Ampheel assembly is held by the gripper of UR10e manipulator keeping the axis horizontal. One end of an inelastic string is attached to the Ampheel in tangential direction as show in Fig. 20 (a) while the other end is attached to the digital spring gauge which is hooked to the fixed support. The robot gripper is then moved upward vertically till the spring gauge displays load more than 5 kg. It is evident from Fig. 20 (b) that the Ampheel assembly is safe in cantilever bending till the radial loading of 5.450 kg (~ 54.5 N) which produces 54.5 kg-cm torque on the interfacing shaft.

Now to check the bending strength, the inelastic string is attached radially to the Ampheel as shown in Fig. 20 (c) and the same procedure is repeated. From Fig. 20 (d) it is seen that the Ampheel assembly is able to withstand the 5.290 kg (~52.9 N) of radial load. Further to estimate the failure strength of the interfacing shaft, the UR10e is further moved upward to increase the load on the assembly till the failure. The interacting shaft breaks at 12.38 kg which is almost 123.8 N as shown in Fig. 20 (e). It is also seen that the shaft breaks at the area which is identified as weaker section from FEA simulation i.e. the intersection of shaft body and the cylindrical protrusions.

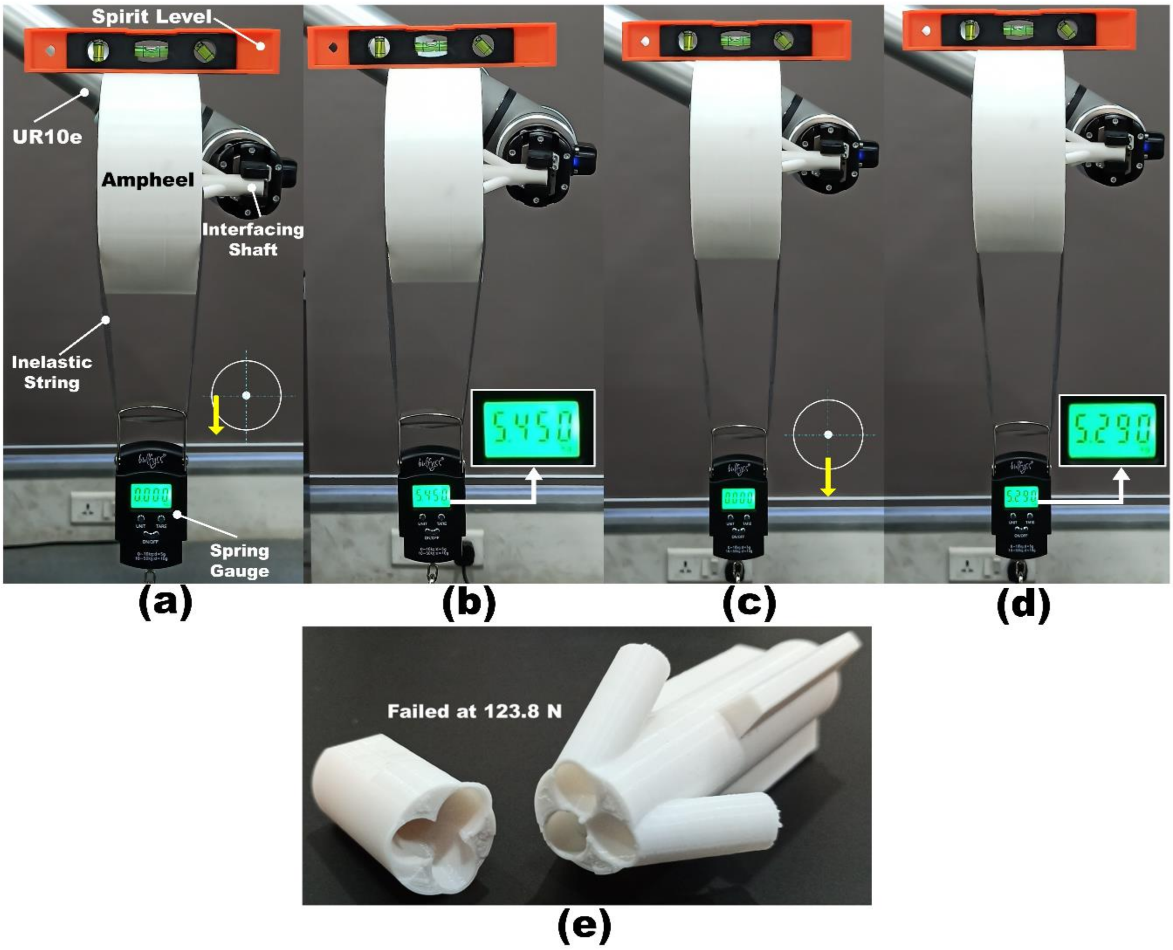


Fig. 20. Experimental setup (a) initial set up for tangential loading test, (b) tangential loading of more than 5 kg, (c) initial set up for radial loading, (d) radial loading of more than 5 kg

4. Conclusion

Present research work delves into the intricate realm of conceptualization and optimization of a bioinspired amphibious locomotion mechanism for mobile robot. Through a comprehensive exploration of existing literature, conceptual frameworks, and innovative design strategies, the key principles governing the integration of terrestrial and aquatic locomotion systems have been elucidated. Out of all amphibious animals, the aquatic locomotion mechanism of fresh water turtle is found to be more relevant to incorporate in the proposed design. The major contribution of the present research work is the development of an innovative bioinspired amphibious locomotion mechanism called "Ampheel" which is equipped with soft actuators to mimic the aquatic locomotion of fresh water turtle. The distinguished feature of the Ampheel is abstraction of soft pneumatic actuator bio-inspired from the legs of the turtle which extend and retract from the body as well as provide rowing action to locomote in water. Ampheel utilizes the wheel rolling action for terrestrial locomotion while for aquatic setting it uses the rowing action of extended soft pneumatic actuators generated by rotation of the Ampheel and thus integrate both terrestrial and aquatic locomotion by single driving system. Topology optimization has been conducted to reduce the weight of the initial design of Ampheel and a significant weight reduction of 64.7% is achieved which reinforces the efficiency and effectiveness of the design improvement. The interfacing shaft is designed in a way such that it powers the Ampheel for rotational motion and also facilitates the soft pneumatic actuator with supply of air flow during the rotational motion of Ampheel. The proposed Ampheel is topologically optimized design. The

Ampheel assembly is experimentally tested for bending and torsional loading and found safe till the designed load of 50 N. The bending strength of the interfacing shaft is also derived experimentally by destructive testing. The FEA simulation results and the experimental observations strengthen the proposed design of Ampheel to be applied on the field. The proposed Ampheel utilizes the rolling action of wheel for terrestrial locomotion and hence struggle to travel on the terrain with pick-valley. Despite of the limitation of wheel, Ampheel is advantageous in amphibious locomotion using single driving system for both the environment effectively and efficiently.

Further experimental investigation of the thrust force produced by Ampheel while moving in aquatic environment with extended soft actuator can be considered as scope of extension of present study. Also, the structural and geometrical optimization of soft pneumatic actuator to improvise the axial expansion for enhancing the aquatic motion characteristics will be another interesting extension of this study. The proposed design of Ampheel contributes to advancing the capabilities of mobile robots in traversing diverse environments and widen the scope of further research in multimodal locomotion mechanism for mobile robots.

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