STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 3, 2026
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Review JoPC

Design and Performance Evaluation of PLA-based Umbrella Wheels for Stair-Climbing Robotic Applications

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Abstract

Staircase climbing robots require a complex design capable of navigating various stair configurations. A crucial component of such robots is the wheel mechanism. This paper focuses on the umbrella wheel mechanism and its application in staircase climbing robots. In this study, a PLA–based umbrella wheel structure is developed and fabricated using fused deposition modeling (FDM) for application in stair-climbing robots. The umbrella wheel geometry enables transformation from a circular rolling configuration on flat surfaces to an expanded segmented profile for step climbing. A mathematical model describing the kinematics of the four-segment umbrella wheel mechanism is formulated to predict segment positions, velocities, and accelerations during operation. The kinematic model was compared with ADAMS multibody simulation results and qualitatively examined using a 3D-printed prototype during stair-climbing tests. Structural performance of the 3D printed PLA-based wheel is evaluated using finite element analysis in ANSYS to determine stress distribution under stair-climbing and flat-surface loading conditions. Simulation results reveal that peak von Mises stresses occur near the junctions of long and short arms, while remaining within safe limits for the selected PLA-based material. The combined results show that the 3D printed PLA-based umbrella wheel can achieve sufficient mechanical strength, stable deformation behavior, and good step engagement, which can be used for the purpose of stair climbing. The proposed approach identifies the potential of additively manufactured structures in lightweight, customizable and functionally adaptive robotic mobility systems.

Keywords: Umbrella wheel mechanism, staircase, climbing robot, mathematical modelling, ADAMS, structural analysis, 3D printer, PLA

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Received Date: April 13, 2026
Accepted Date: April 23, 2026
Published Date: May 14, 2026

Citation: Penta Srinivas, G.Yedukondalu, Bondili Harshith Singh. Design and Performance Evaluation of PLA-based Umbrella Wheels for Stair-Climbing Robotic Applications. Journal of Polymer & Composites. 2026; 14(Special Issue 3): S808–S824p.

INTRODUCTION

Stair-climbing robots have attracted significant research interest due to their broad spectrum of applications in search and rescue, inspection, surveillance and service robotics [1, 2]. Unlike conventional mobile robots which work on flat surfaces, stair-climbing robots have to deal with discontinuous geometries and different riser heights and abrupt changes in elevation while maintaining stability and traction. The mechanism of locomotion thus plays an important role in determining the overall performance, reliability and energy efficiency. As a result, a lot of research efforts have been focused on the development of special locomotion mechanisms that can overcome the obstacles at stairs effectively [3, 4].

Current stair-climbing robots employ alternative locomotion mechanisms such as tracked robots, legged robots, wheeled robots and hybrid wheel-leg robots [3–6]. Tracked and legged systems typically provide an excellent adaptability to the surfaces but are hampered by rising the mechanical complexity and weight of the system and growing power usage. Alternatively, wheel-based locomotion systems possess several benefits such as structural simplicity, enhanced efficiency and controllability. The traditional circular wheels, however, have a disadvantage of not being able to overcome vertical obstacles like the stair risers. To address this drawback, a few modified concepts of wheels like the star wheels, segmented wheels, omnidirectional wheels and wheel-leg hybrid designs have been suggested [7–11].

The umbrella wheel mechanism is one of such solutions that have been identified as a promising solution in stair climbing applications. The umbrella wheel consists of numerous pieces of rim joined by linkages which open and close similar to an umbrella. This configuration lets the wheel to keep a circular profile for efficient rolling on flat surfaces and to generate protruding segments to engage the edges of the stairs in climbing [12, 13]. Previous studies on umbrella wheels and related morphing wheel mechanisms have generally been focused on conceptual design, kinematic modeling and dynamic simulation to show the feasibility of motion [12–15]. Nevertheless, the structural performance of umbrella wheel mechanisms has received comparatively little attention, especially when such mechanisms are fabricated using additively manufactured materials.

Simultaneously, additive manufacturing systems, especially fused deposition modeling (FDM), have become widely accepted in producing complex polymer parts in the engineering and robotic fields. The process allows quick prototyping, light-weight structural design, and internal geometries that are customizable and minimize waste of material. Specifically, PLA has been extensively employed in FDM due to its high printability, dimensional stability and functional prototyping capability. Consequently, FDM-printed PLA parts have emerged as viable options in robotic frameworks of lightweight and initial load-carrying. Despite these benefits, the majority of reported research on stair-climbing mechanisms still focuses on mechanical design and motion performance [7–15], whereas the structural behavior of additively manufactured wheel mechanisms during operational loading conditions is under-researched.

Inspired by this void, the current paper explores an umbrella wheel mechanism made of PLA fabricated by FDM to be used in stair-climbing robots. The paper aims at developing geometric design, kinematic model formulation, and structural performance in a multibody dynamic simulation and finite element analysis and experimental analysis. Accordingly, the next section presents the problem statement and describes the geometry of the proposed four-segment umbrella wheel mechanism, which forms the basis for subsequent modeling and performance evaluation.

Literature Survey

Simon Iversen et al. [5] presents umbrella wheel as a design in climbing stairs and traversing obstacles. In this paper, the design of climbing stairs using a segmented wheel is demonstrated. The wheel can be separated in that way that is can go up the stairs and over the obstacles which really exist in a human environment. It also allows the wheel to be circular whenever rolling on smooth surfaces.

C. Lin et al. [6] proposed a stair climbing robot having variable wheel Mechanism. The paper introduces a stair climbing robot whose wheel system can be modified depending on the size of the stair step. It has a design that consists of a set of wheels that in turn can be made longer or shorter to give stability and balance on the stairs, and a mechanism of adjustable suspension that can be adjusted to suit different loads.

W. Xiong et al. [7] covered the research in the designing and analysis of a new robot to climb up the stairs with the assistance of a roller mechanism. The paper describes the design and analysis of a robot which has the ability to climb up the stairs through a roller system and it has a series of passive rollers which are attached to a support frame that provides an option of either up-stairs climbing or down-stairs climbing. The robot will also be capable of climbing the stairs by rolling its rollers up the stairs and the supporting structure will follow along the movement of the rollers to provide stability. The study also addresses the problems of kinematics and dynamics of the roller mechanism and the control strategy of the robot.

Z. Guo et.al [8] suggested a stair climbing robot which has the Omnidirectional Wheels. This paper proposes a climbing robot using omnidirectional wheels which has the ability to move in all directions and rotate on the vertical axis to provide power to the robot. The aids fitted on the robot will be an inertial measurement unit (IMU) and a laser distance sensor, which will allow the robot to avoid and detect obstacles and stabilize them on stairs. The manipulation of the robot is another subject of the paper and it applies the feedback and feedforward control to achieve stability and efficiency.

Q. Wei et.al [9] suggested the design and optimization of a stair climbing robot that is controlled on omnidirectional wheels. The current paper is a proposal of stair climb omnidirectional wheel-based robot, the choice of which was a stair climb to increase stability and reduce vibrations during stair climb through a suspension system. The robot can transport a payload up to 30 kg with up to 200 mm high stairs. The study also presents the optimization of the design parameters of the robot which includes the size of the wheel, the stiffness of the suspension, and the location of the payload with the help of a genetic algorithm. The results indicate that the streamlined design improves the performance of the robot when climbing stairs in terms of efficacy and steadiness.

S. Guo et al. [10] reported the design and Implementation of a stair-climbing robot utilizing wheel-leg hybrid mechanism. The mixed system of stair climbing robot given in this paper is one that incorporates the use of wheels and legs to enhance stability and movement capabilities of the staircases. The omnidirectional wheels and four adjustable legs that can be adjusted in length and angle to fit into the stairs shape give the robot a combination of both. Another aspect that is brought out in the study is the means of controlling the robot; a combination of position feedback and impedance control that makes the robot steady and reduces the vibration level when climbing the stairs.

Sri Harsha Turlapati et al. [11] solved the desperate situation of robots treading stairs in an urban environment, particularly in the task of Urban search and Rescue (USAR). This would play a critical role in making robots useful in case the need arises to use them during emergencies where the use of stairs is usually a challenge. The authors conducted a lot of numerical simulations and experimentation in order to demonstrate that their design was effective. They tested the robot on various stair pitches and they established that the robot could climb stairs with a pitch angle of approximately 20 degrees to 35 degrees. This range is exhibited in real life through this versatility, and power of the robot.

Simon Iverse et al. [12] introduced a hybrid model of the Umbrella Wheel, which combines continuous time behavior in rolling and discrete time effects on stairs. This model in conjunction with the measured wheel angle estimates contact and height upon the stairs.

J. L. Ordoñez-Avila et al. [13] discussed the effect of the wheel geometry on the performance of stair-climbing mobile robots. Dynamic simulations were used to analyze the kinematics and dynamics of the robot and provide a correlation between the geometry of the wheel legs and the success of the robot in climbing the stairs.

Valeria Rosales-Garcia et al. [14] presented the design of a physical prototype on a stair-climbing wheel with legs. The study focuses on the challenge of overcoming obstacles such as stairs with this new design of a wheel, and the study proves that the prototype was effective in climbing the stairs.

D.K. Seo et al. [15] introduced a new wheel-leg system to climb stairs with a focus on the kinematics and the dynamics of curved-spoke wheels and interaction with motor-driven tires. The paper identifies the design specifications needed in climbing with a single wheel and the required friction coefficients.

Haoran Wang et al. [16], introduced the SWhegPro3, which is a three-impeller wheel-leg transformable robot that employs self-locking electric push rods to switch between the modes that improve load capacity and stair-climbing capability. To validate their design and control strategy, the authors obtain a model to compute the optimal configuration of the wheel-leg module to different stair sizes, which is supported by simulation and field experimentation.

Shuaiby Mohamed et al. [17] introduced a quad omni-wheeled mobile robot which uses omni wheels and linear servo actuators showing that the robot has the ability to climb up the stairs and move in different directions. This work involves the development of a prototype robot and confirms that the robot can climb the stairs by simulating SolidWorks and MATLAB Simscape Multibody, which helps in the classification of stair-climbing mechanisms in robotics.

Tongxin Cui et al. [18] focused on a four-wheel mobile robot that used a passive star-wheel design to climb stairs, examining the conditions to overcome obstacles and derived driving torque about the statical analysis. They confirm stability of the robot when climbing stairs using simulations and physical experiments, efficiency of the energy is ensured by measuring torque use under defined loads.

Isaku Nagai et al. [19] introduced a power-aided carrier cart which used Tri-star wheel to climb stairs and move on flat terrains. The device design consists of 3 drive wheels, and a load sensor to control motors according to the pulling force exerted by the user.

Xueshan Gao et al. [20], documented a mathematical model that was founded on classical mechanics to study dynamic principles during obstacle climbing. The dynamic stability analysis considers the interaction of the forces between the track, track edge and stair steps thereby giving information about the stability of the robot.

FDM-fabricated PLA components have attracted considerable attention in lightweight robotic and structural applications due to their ease of manufacture and design flexibility. Recent reviews have shown that process parameters, including layer height, raster orientation, infill density, and nozzle and bed temperatures, strongly influence the mechanical performance, defect formation, and anisotropic response of printed parts [21]. These studies provide a useful basis for selecting print orientation and fabrication settings for load-bearing robotic components. They also report representative tensile, flexural, and thermal property ranges for PLA and other commonly used FDM polymers, which are directly relevant to evaluating the structural integrity and stress margins of the proposed umbrella wheel.

Therefore, a need exists for systematic investigation of the structural performance of 3D printed PLA-based umbrella wheel mechanisms in stair-climbing robots. In this work, a PLA-based four-segment umbrella wheel is developed using FDM. A mathematical model is formulated to describe the kinematics of the mechanism and compared with multibody dynamic simulation results in ADAMS. Finite element analysis using ANSYS is employed to evaluate stress distribution and structural integrity under stair-climbing and flat-surface conditions. The objective is to establish the feasibility of 3D printed PLA-based umbrella wheels as lightweight, mechanically robust, and adaptable locomotion components for stair-climbing robotic systems.

MATERIALS AND METHODS

Staircase Climbing Robot

Figure 1 depicts the structural model of the robot designed to climb staircases. Its wheeled design gives the robot the option to go upstairs, which is made easier through a special wheel structure which allows the robot to move across every staircase.

The fundamental concept of the Umbrella Wheel design is to maintain a circular wheel for traveling on even surfaces and to modify it to enable obstacle traversal, such as climbing stairs, when required. Our design approach involves dividing the outer section of the wheel into multiple segments, referred to as wheel segments, which extend outward from the axle to form spokes.

Design Concept of Umbrella Wheel Mechanism

Figure 2 displays a 3D model of the Umbrella Wheel mechanism, which comprises a disc and a runner connected to the main axle of the wheel. The disc is attached to the axle and the runner is not attached, allowing the arms and the wheel segment rims to lengthen or shorten. One way of extending or retracting the arms is by lifting them up like opening an umbrella thus the name of the mechanism. It is necessary to mention that short arms are half as long as long arms, which does not allow the wheel segments to turn in the direction of the axle during arms extension. Consequently, the rim of the wheel segment is displaced in a radial direction either towards or away from the axle.

The umbrella wheel mechanism employs a design that employs metal arms linked to a runner. The actuator that powers the mechanism is connected to the runner. The metal arms are designed to expand and contract, resembling an umbrella, facilitating the mechanism's movement.

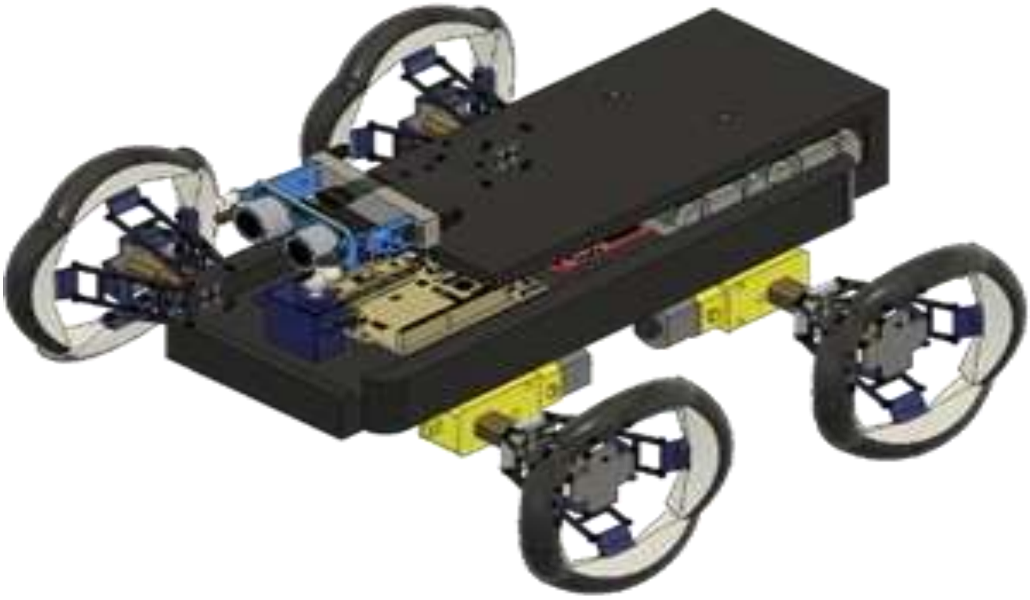

Figure 1. Staircase climbing robot.

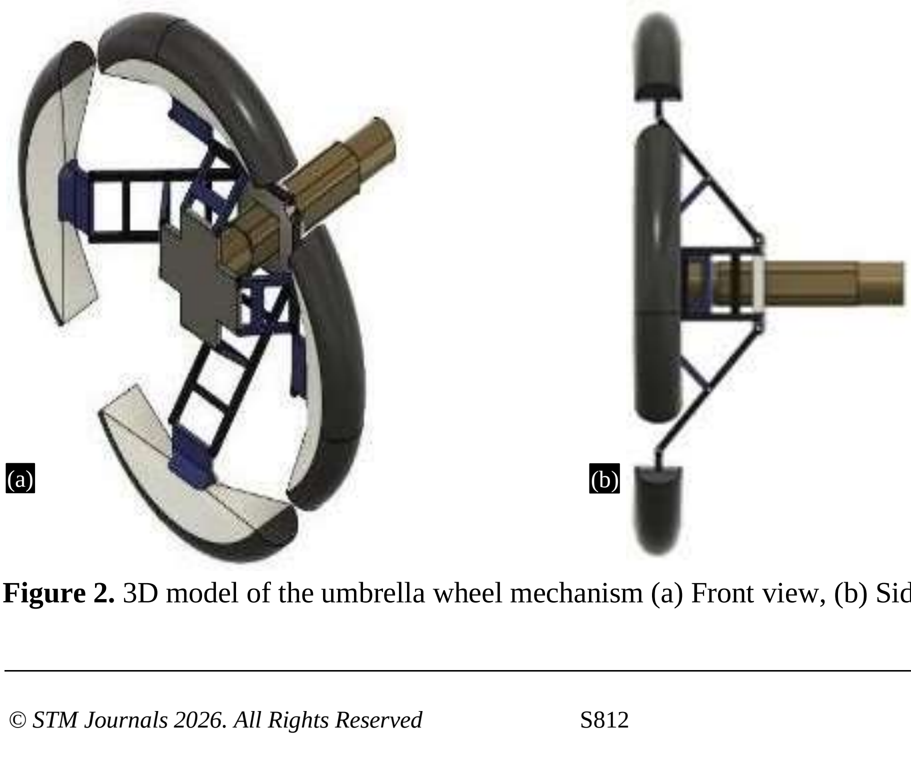

Figure 2. 3D model of the umbrella wheel mechanism (a) Front view, (b) Side view.

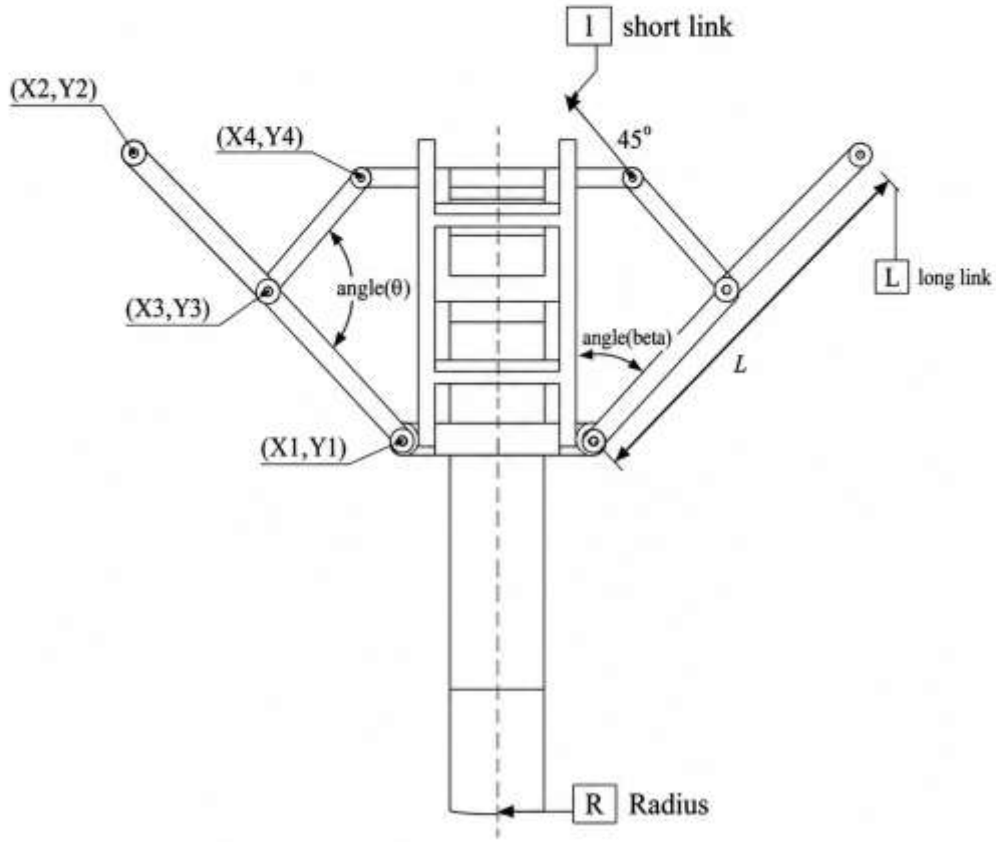

Figure 3. Line diagram of wheel mechanism.

Mathematical Modelling of Umbrella Wheel Mechanism

The mathematically model the four segment Umbrella Wheel Mechanism is to use a set of equations that describe the position, velocity, and acceleration of each segment of the wheel.

Let R be the radius of the wheel, L be the length of the long arms, and l be the length of the short arms. Where θ is the angle that the central axle takes with the long arms and φ is the angle the long arms take with the short arms as indicated in Figure.3.

The position of each segment can be described by the following equations:

$$x_1 = R\cos(\theta)$$

$$y_1 = R\sin(\theta)$$

$$x_2 = x_1 + L\cos(\theta)$$

$$y_2 = y_1 + L\sin(\theta)$$

$$x_3 = \frac{l}{2}\cos(\theta + \varphi)$$

$$y_3 = \frac{l}{2}\sin(\theta + \varphi)$$

$$x_4 = x_3 + l\cos(\theta - \varphi)$$

$$y_4 = y_3 + l\sin(\theta - \varphi)$$

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

Where (x_1, y_1) is the position of the central axle, $(x_2, y_2)$is the position of the end of the long arms, and (x_3, y_3) and (x_4, y_4) are the positions of the end of each short arm.

The velocity of every part can be determined as a result of differentiating the position equations with respect to time:

$$\mathrm{vx}_1 = -\mathrm{R}\sin(\theta)\dot{\theta}$$

$$\mathrm{vy}_1 = \mathrm{R}\cos(\theta)\dot{\theta}$$

$$\mathrm{vx}_2 = \mathrm{vx}_1 - \mathrm{L}\sin(\theta)\dot{\theta}$$

$$\mathrm{vy}_2 = \mathrm{vy}_1 + \mathrm{L}\cos(\theta)\dot{\theta}$$

$$\mathrm{vx}_3 = -\frac{\mathrm{l}}{2}\sin(\theta + \varphi)(\dot{\theta} + \dot{\varphi})$$

$$\mathrm{vy}_3 = \frac{\mathrm{l}}{2}\cos(\theta + \varphi)(\dot{\theta} + \dot{\varphi})$$

$$\mathrm{vx}_4 = \mathrm{vx}_3 - \mathrm{l}\sin(\theta - \varphi)(\dot{\theta} + \dot{\varphi})$$

$$\mathrm{vy}_4 = \mathrm{vy}_3 + \mathrm{l}\cos(\theta - \varphi)(\dot{\theta} - \dot{\varphi})$$

Where, $\dot{\theta}$and $\dot{\varphi}$ are the angular velocities of the central axle and the long arms, respectively.

The acceleration of every segment is obtainable by differentiating the equations of velocity with regard to time:

$$\mathrm{ax}_1 = (-\mathrm{R}\cos(\theta)\dot{\theta}^2) - (\mathrm{R}\sin(\theta)\ddot{\theta})$$

$$\mathrm{ay}_1 = (-\mathrm{R}\sin(\theta)\dot{\theta}^2) - (\mathrm{R}\cos(\theta)\ddot{\theta})$$

$$\mathrm{ax}_2 = \mathrm{ax}_1 - \mathrm{L}\cos(\theta)(\dot{\theta})^2 - \mathrm{L}\sin(\theta)(\ddot{\theta})$$

$$\mathrm{ay}_2 = \mathrm{ay}_1 - \mathrm{L}\sin(\theta)(\dot{\theta})^2 + \mathrm{L}\cos(\theta)(\ddot{\theta})$$

$$\mathrm{ax}_3 = -\frac{\mathrm{l}}{2}\cos(\theta + \varphi)(\dot{\theta} + \dot{\varphi})^2 - \frac{\mathrm{l}}{2}\sin(\theta + \varphi)(\ddot{\theta} + \ddot{\varphi})$$

$$\mathrm{ay}_3 = -\frac{\mathrm{l}}{2}\sin(\theta + \varphi)\left(\dot{\theta} + \dot{\varphi}\right)^2 + \frac{\mathrm{l}}{2}\cos(\theta + \varphi)(\ddot{\theta} + \ddot{\varphi})$$

$$\mathrm{ax}_4 = \mathrm{ax}_3 - \mathrm{l}\cos(\theta - \varphi)\left(\dot{\theta} - \dot{\varphi}\right)^2 + \mathrm{l}\sin(\theta - \varphi)(\ddot{\theta} - \ddot{\varphi})$$

$$\mathrm{ay}_4 = \mathrm{ay}_3 - \mathrm{l}\sin(\theta - \varphi)\left(\dot{\theta} - \dot{\varphi}\right)^2 + \mathrm{l}\cos(\theta - \varphi)(\ddot{\theta} - \ddot{\varphi})$$

Where, $\dot{\theta}$, $\ddot{\theta}$, $\dot{\varphi}$, and $\ddot{\varphi}$ are the angular velocity and angular acceleration of the mechanism's driving link and driven link, respectively.

The equations can be applied to the kinematics of the four segment Umbrella Wheel Mechanism and optimise the performance in various situations.

Dynamics of Umbrella wheel mechanism

The four segment umbrella wheel mechanism has dynamic equations that can be derived by applying Newtons second law that stipulates that the total force applied on an object equals the product of the mass of the object and the acceleration. Here, every part of the mechanism is considered an independent object.

The forces on segment-1 are the force caused by gravity and the force caused by long arms:

$$\sum F_1 = F_L - m_1 g$$

Where F_L is the force conveyed by the long arms, m_1 is the mass of segment-1, and g is the acceleration due to gravity.

In segment-2 the forces acting on that segment are the force due to gravity, the force to be transmitted via the long arms, the forces to be transmitted via the short arms:

$$\sum F_2 = F_L + F_3 + F_4 - m_2 g$$

Where F_3 and F_4 are the forces provided by the short arms, and m_2 is the mass of segment-2.

The forces which are applied to it in a segment-3 are the forces which are transmitted by the short arm-1 and the force which is transmitted by the long arm:

$$\sum F_3 = F_L - F_3 - m_3 g$$

Where m_3 is the mass of segment-3.

In segment-4, forces acting on it consist of the force passed on the short arm-2, and the force passed on the long arm:

$$\sum F_4 = F_L - F_4 - m_4 g$$

Where m_4 is the mass of segment-4.

The equations of position and acceleration obtained above can be solved to calculate the long arm and short arm forces.

Using these force equations and the acceleration equations, the dynamic equations of motion can be written as follows:

For segment 1

$$m_1(ax_1) = F_L - m_1 g$$

$$m_1(ay_1) = 0$$

For segment 2

$$m_2(ax_2) = F_L \cos(\theta) + F_3 \cos(\theta + \varphi) + F_4 \cos(\theta - \varphi) - m_2 g\cos(\theta)$$

$$m_2(ay_2) = F_L \sin(\theta) + F_3 \sin(\theta + \varphi) + F_4 \sin(\theta - \varphi) - m_2 g\sin(\theta)$$

For segment 3

$$m_3(ax_3) = -F_3 \cos(\theta + \varphi) - m_3 g\cos(\theta + \varphi)$$

$$m_3(ay_3) = -F3 \sin(\theta + \varphi) - m_3 g\sin(\theta + \varphi)$$

For segment 4

$$m_4(ax_4) = -F_4 \cos(\theta - \varphi) - m_4 g\cos(\theta - \varphi)$$

$$m_4(ay_4) = -F_4 \sin(\theta - \varphi) - m_4 g\sin(\theta - \varphi)$$

These dynamic equations can be used to study the behavior of the mechanism under different conditions and to optimize its performance.

SIMULATION OF UMBRELLA WHEEL MECHANISM

The umbrella wheel mechanism is recreated as two dimensional within the $x - y$ plane and that z - coordinate is fixed within the motion simulation. The umbrella angle with reference to the ground can be improved to get the desired step size to simulate the climbing movement of the mechanism. An increase in the angle will lead to an increase in the step size and a decrease in the angle will lead to a decrease in the step size. This implies that the umbrella wheel system will be able to ascend more and at a greater angle, but the movement may be slower because of the frictions of the ground. Conversely, the smaller the angle, the smaller the step size will be, however the movement could be quicker because the ground does not provide as much resistance.

Step size is also influenced by the diameter of wheels, length of connecting links and friction between the wheels and the ground. An increased diameter of the wheel and increased connecting links may lead to an increased step size, whereas increased friction between the ground and the wheels may lead to a decreased step size. These factors are to be taken into consideration when designing and simulating the umbrella wheel mechanism to attain optimum functionality.

The simulation analysis of the robot in terms of stair climbing dynamics was performed based on the earlier modeling analysis; 3D virtual prototype modeling and ADAMS software were used to simulate the analysis. The simulation prototype model is shown in Figure 4. In the ADAMS software, the mechanism is modeled using rigid bodies, and each rigid body is divided into one or more segments. These segments are connected to each other by joints, which allow them to move relative to each other. Segment-1 is the fixed segment that is connected to the ground using a fixed joint. Segment-2 is connected to segment-1 using a revolute joint, which allows it to rotate around segment-1. The simulation results are obtained as shown in Figure 5.

In Figure 5(b), the centre of mass is an important parameter as it represents the point where the mass of the shaft is concentrated. The position of the centre of mass determines the overall motion of the mechanism. In Figure 5(c), the first segment is represented with red colour line and connecting the umbrella to the shaft. The second segment is represented with blue colour line and connecting the

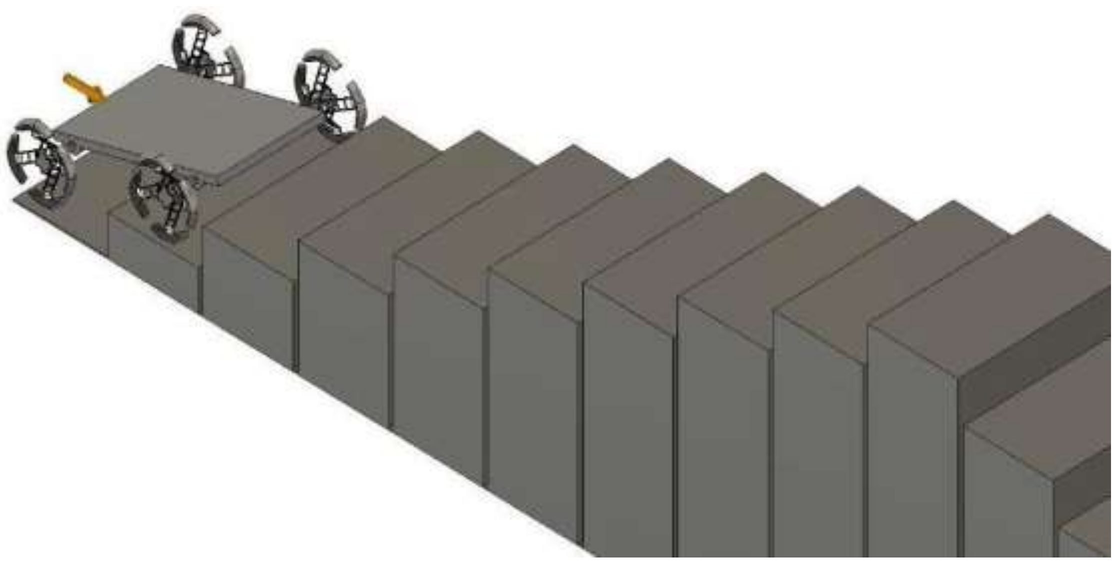

Figure 4. ADAMS simulation drawing of climbing stairs.

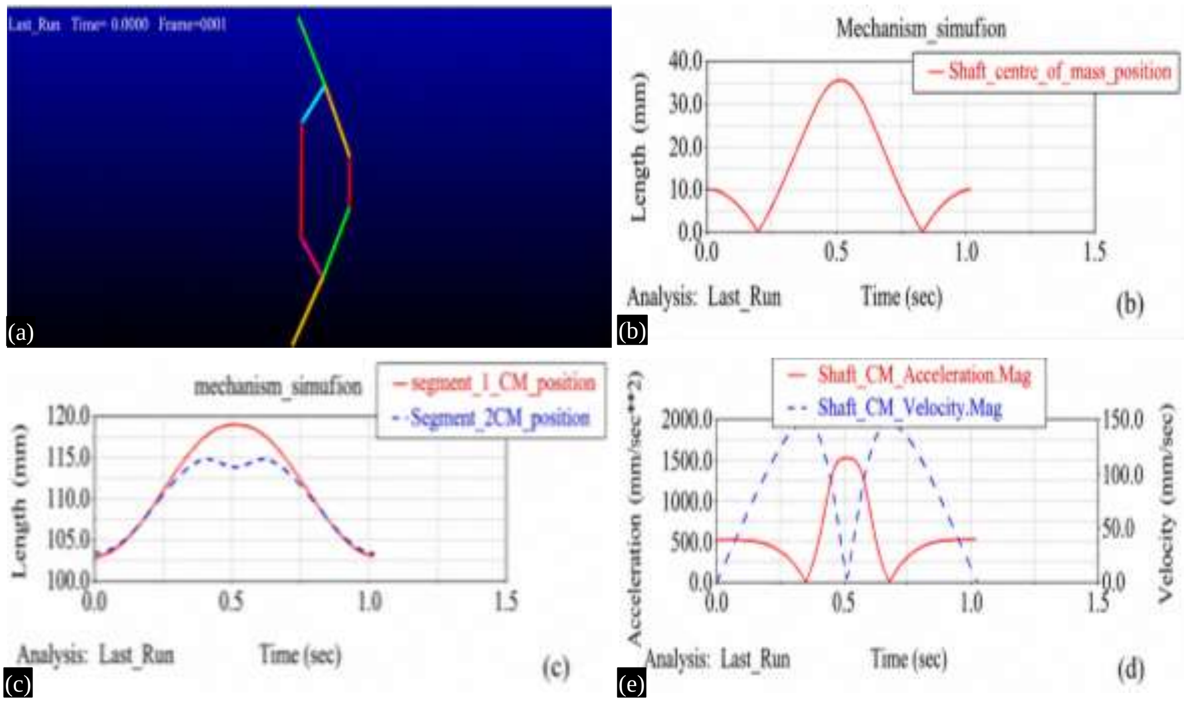

Figure 5. Umbrella wheel mechanism simulation graphs.

wheels to the first segment. These graphs are providing information about the motion of the first and second segment of the mechanism. In Figure 5(d), the red and blue lines are the shaft velocity and acceleration.

Structural Analysis of Umbrella Wheel Mechanism

Polylactic Acid (PLA) was selected as the primary material for fabricating the umbrella wheel using fused deposition modeling (FDM) due to its ease of processing, dimensional stability, low warpage, and adequate mechanical strength for prototyping and functional testing. PLA has a common tensile strength of 50–60 MPa, elastic modulus of 2.3–3.8 GPa and compressive strength of approximately 60 MPa and is applicable in moderate load robotic applications.

The structural analysis results presented in Figures 6 and 7 demonstrate that the areas of localized stress concentration are mainly at the curved outer parts of the umbrella wheel, and around the joint areas between the spokes and the centre hub. When the wheel is in contact with stair edges and uneven surfaces the bending and contact stress is higher in these areas. PLA is a comparatively fragile thermoplastic in comparison with the engineering polymers like ABS or Nylon and therefore, special care has to be taken to ensure that the von Mises stress at the most critical areas is way less than the yield strength of the material and there should be a reasonable margin of safety.

Figure 8 shows that the distribution of stress in stair climbing is not uniform and depends on the interactions of self-weight, external load and gravity loading. This acting justifies the modelling of PLA as linear elastic isotropic material to perform initial structural analysis. Nevertheless, anisotropy of the FDM-printed PLA should be considered because the inter-layer bonding is generally lower than the in-plane bonding. The printing orientation therefore must be selected so that the major stress directions as far as possible coincide with the filament deposition paths especially the curved arms and at the hub-spoke junctions.

To enhance load-bearing capacity and reduce the risk of crack initiation at stress concentration zones, higher infill density (≥70%), multiple perimeter shells, and increased wall thickness are recommended for the umbrella wheel segments. Also, reinforcement by the local means of thickness of cross-sections or filleted transitions at joint interfaces can be effective in eliminating stress concentration effects in the simulations.

There is also a thermal restriction on PLA, with a glass transition temperature of around 60o C. Because stair-climbing robots can work in places where frictional heating or ambient temperature increase is involved, the operating temperatures should not exceed this level otherwise stiffness may be reduced, and creep deformation may happen. To use with larger loads or higher temperatures, composite filaments made of PLA may be used and enhance stiffness and strength without compromising printability.

In general, the structural analysis supports the notion that the proposed umbrella wheel mechanism can be applied in the circumstances of the proposed loading conditions and under the assumption that the amount of stress does not exceed permissible values and the reinforcements with the help of printing and geometric requirements are used. The stress patterns as observed in Figures 6–8 are used in the optimization of materials used and structure of the wheel in a reliable stair-climbing behavior.

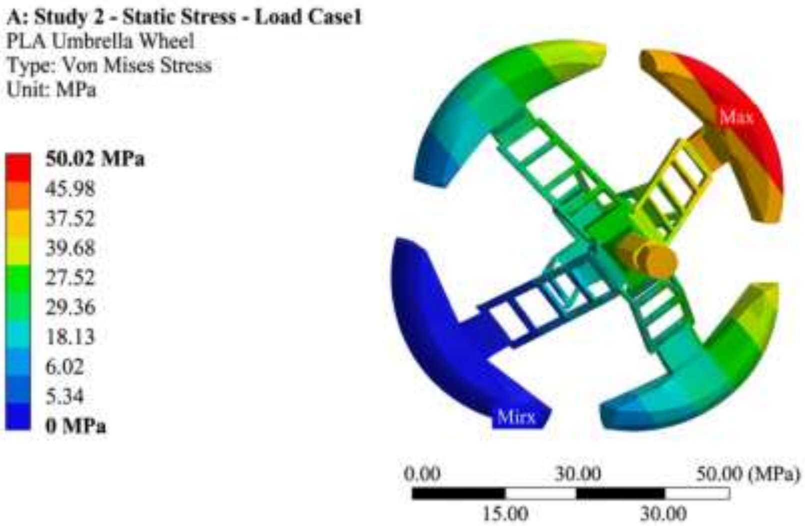

Figure 6. Stress concentration during step climbing.

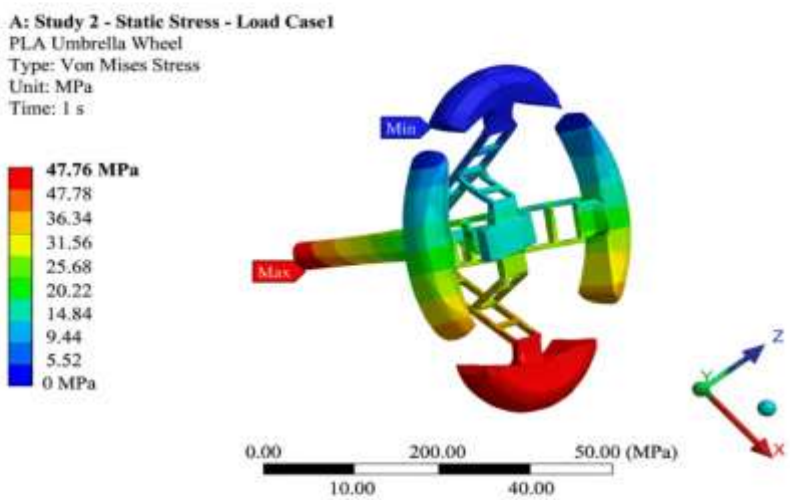

Figure 7. Stress concentration on flat surface.

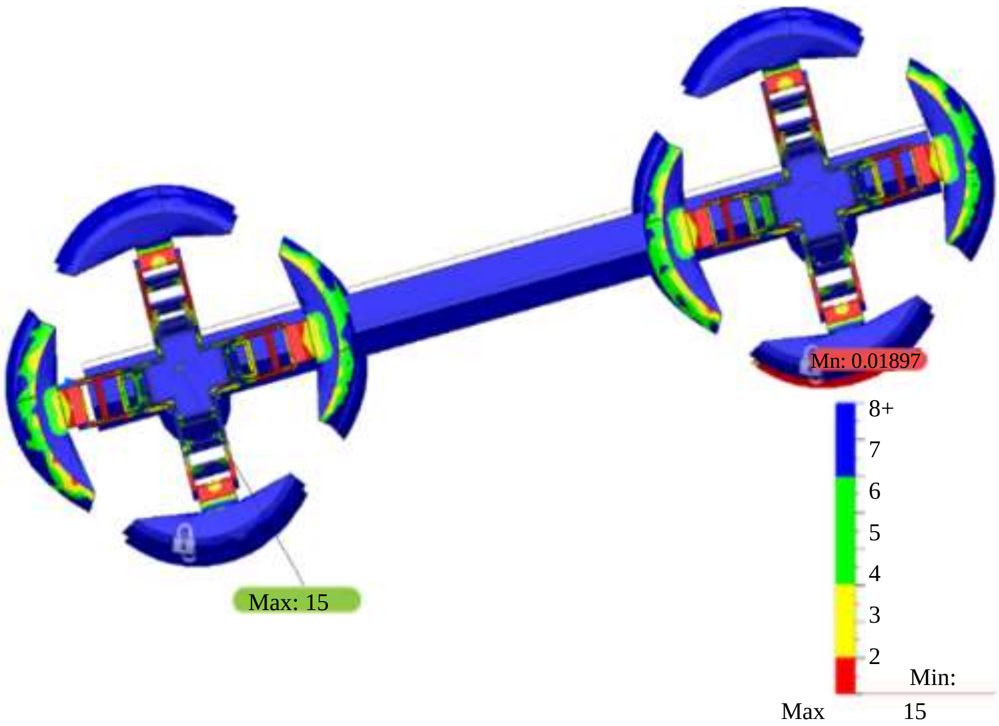

Figure 8. Stress distribution on the wheel.

Along with the statical stress test, the long-term service behaviour of PLA-based wheel segments fabricated with FDM, should be viewed with care as well. Cyclic bending, and repetitive contact between edges are expected to cause the onset of the most severe failure modes on the hub-spoke junctions, curved rim segments, pin-joint interfaces, and interlayer boundaries, where cyclic bending and repeated edge contact can facilitate the development of fatigue cracks, local wear, and progressive stiffness loss.

Since FDM parts are built by adding a layer at a time, their strength is affected not just by the properties of the bulk material used but also by the quality of interlayer bonding, internal porosity, the orientation of the print, and sensitivity to notches.

Both, material assumptions and printing parameters are also sensitive to the computed stress distribution. Elastic modulus, tensile strength, and effective anisotropy of the printed PLA material, and raster orientation changes can change local stiffness and reorient the stresses around the highest loaded joints. Practically, a decrease in the quality of interlayer bonding or infill density can cause the response to move towards distributed bending to more localized stress concentrations and delamination prone behavior.

Material Selection and Printing Methodology

Polylactic Acid (PLA) filament was chosen as the base material on which the umbrella wheel components were to be fabricated through the use of fused deposition modeling (FDM). PLA was selected because of its simplicity to work with, dimensional stability as well as low warpage and sufficient mechanical strength to be used in functional prototyping and robotic use with moderate loads. The common mechanical characteristics PLA have a tensile strength of 50–60 Mpa, elastic modulus of 2.3–3.8 Gpa, compressive strength of around 60 Mpa, and these are just enough to preliminary assess the structure of a robotic wheel by using it.

Commercially available PLA filament with a diameter of 1.75 mm was used for all the printed components. The three-dimensional CAD models of the umbrella wheel segments, long arms, short arms, hub, runner and end caps were developed using CAD software, and implemented in STL format. The STL files were processed using slicing software to create the printer toolpaths.

All the components were made through a desk top FDM 3D printer. The choice of the printing parameters was made according to the initial experiments to guarantee a high quality of surfaces, correct dimensions, and mechanical strength. The nozzle diameter was 0.4 mm, and the height of the layer was 0.2 mm. The printing temperature and the temperature of the heated bed were established to 200°C and 60°C respectively. The printing speed was taken to 50 mm/s. A grid infill pattern was taken to have infill density of 70% to enhance stiffness and load-bearing capacity of the wheel segments. All the parts were finished with three perimeter shells to increase the strength of the surface and minimize the formation of cracks in the most stressed areas.

The segments of the wheel and the structural arms were additively manufactured in a flat position to enhance the in-plane strength in the major load paths. The parts were printed and checked visually on defects and dimensional variation. Light manual finishing was used to remove minor surface irregularities. No post-processing, chemical or thermal was done.

The umbrella wheel assemblies were made and were integrated with printed components by incorporating the metallic threaded rods, fasteners, and ball bearings. The printed end caps were fitted with bearings so that they would rotate smoothly. The umbrella wheel modules were made with the same material and as well as printing parameters to ensure consistency between the assumptions in simulations and experiments.

CASE STUDY OF EXPERIMENTAL VALIDATION OF 3D PRINTED PROTOTYPE

Experimental validation of the kinematic behavior of the expanding-wheel stair-climbing robot was tested using a physical prototype developed using 3D printing as illustrated in Figure 9, to enable the structural integrity of the finite element analysis to be verified by the experiment. This stair height of 7 cm, and the larger wheel diameter of 14 cm are a significant geometric climbing condition (R = h) and hence a conservative case study to prove the viability of the proposed morphing umbrella wheel mechanism.

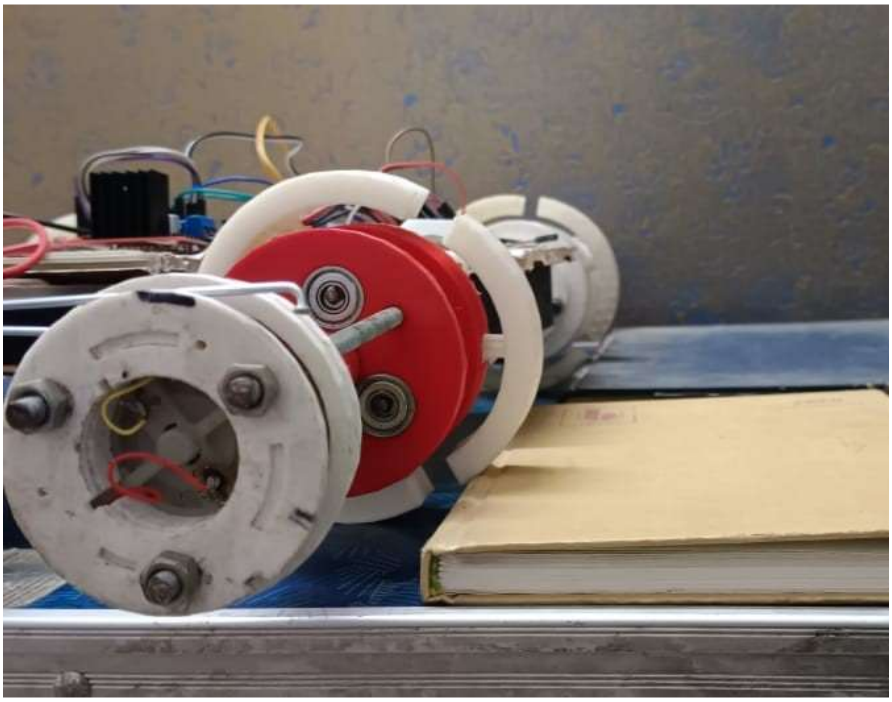

Figure 9. Stair climbing test setup.

The expanding mechanism was smooth to work during testing without apparent imbalance or mechanical interference. The wheels continued to roll on a constant basis with the surface and no structural damage or apparent deformation was evident in the segments of wheels. During the experiments, the wireless Bluetooth between the controller and the robot was stable and responsive, thus allowing real-time actuation of the expansion mechanism to be reliable.

It should be noted that the present experimental study was conducted primarily as a proof-of-concept feasibility investigation rather than as a full system-identification exercise. The physical prototype confirmed the desired opening and closing sequence of the wheel segments, effective stair-edge engagement, and the ability to remain stable in climbing behavior when operating.

DISCUSSION

The kinematic performance of the four-segment umbrella wheel mechanism derived from the analytical formulation shows good qualitative agreement with the multibody dynamics simulation carried out in ADAMS. The predicted and simulated curves exhibit similar trends for the individual wheel segments, indicating that the model is suitable for preliminary kinematic assessment under the present conditions.

The opening and closing of the wheel segments when climbing the stairs enable the effective use of the edges of the steps, and they retain the rolling properties on flat surfaces. These results indicate that the umbrella wheel design is suitable for hybrid rolling-climbing locomotion at the proof-of-concept level.

In 3D printed PLA-based umbrella wheel finite element analysis, it can be seen that stress distribution is not uniform and heavily relies on the nature of contact between the segments of the wheel and the edges of the stairs. Mainly at the curved areas of the outer rim and at the connections between the long and short arms, where bending and contact forces reach the highest points, stress concentration areas are observed locally. At a combined robot and payload mass of 20 kg the von Mises maximum stress is around 50 Mpa, within the normal tensile strength of 50–60 Mpa of FDM-printed PLA. This suggests that the proposed wheel design remains within acceptable stress limits for moderate-load proof-of-concept applications.

The findings also reveal the effects of additive manufacturing properties on structural performance. Despite the fact that PLA is designed as a linear elastic isotropic material to be analyzed at first, FDM-printed components are actually anisotropic because of the layer-by-layer deposition and bonding interlayers. The orientation of printing should therefore be chosen with the large load paths conforming to the direction of filaments, most especially at junctions of hubs and spokes as well as at curved arms. To further increase load-bearing capacity and diminish crack formation at critical points, the density of infill, the thickness of the walls, and the amount of perimeter shells may be increased.

Material wise, PLA is easy to process, dimensionally stable and has low warpage which makes it a good choice in rapid prototyping and testing of functions. It has a relatively low glass transition temperature (55–60^{o}C) and is therefore not useful in high temperature or high friction settings. PLA-based with carbon or glass fibers reinforcement could be used to improve stiffness, strength, and thermal resistances. These materials are predicted to add the factor of safety and retain the FDM printability.

The comparative performance of umbrella wheel can be construed in a light of three competing goals: flat-ground efficiency, stair-climbing stability, and system complexity. In the near-circular mode of operation of the wheel, the mechanism holds the main benefit of the wheeled locomotion, which is a low rolling resistance and less actuator effort in moving along level surfaces. This provides the mechanism with a probable efficiency benefit over tracked and fully legged systems when not climbing, as the latter normally involves either continuous track deformation losses or their extra active degrees of freedom [1–4]. Contrarily, on the stair climbing, the tracked platforms usually offer a larger support polygon and more continuous contact that can enhance the quasi-static stability, and wheel-leg and highly articulated hybrid mechanisms tend to achieve better terrain adaptability. The umbrella wheel thus is a middle ground solution: it is structurally and kinematically less complex than most hybrids, and more step-friendly than a traditional circular wheel.

The mechanism can be scaled but is not a purely geometric scaling problem. The ability to adapt effectively to the various sizes of robots and the real geometry of the stair steps is determined by maintaining important ratios of the dimensions especially the ratio of extended wheel radius and stair riser height, the available reach of the segment tip over the tread depth and adequate clearance of the hub and body during stepping over. Structural mass and the actuator torque needed to make a robot grow exponentially with its size, and section thickness, choice of material, joint geometry, and the size of drives need to be designed as a system instead of scaling identically. Besides that, the real-life staircases can incorporate rounded nosing, overhangs, narrow treads, uneven risers, and surface material differences. In these cases, the suggested mechanism would have an expansion stroke that can be adjusted or modular link-length selections, in addition to perception-based control to adjust the wheel configuration prior to edge contact.

Overall, the combined analytical modeling, dynamic simulation, structural analysis, and proof-of-concept experimental testing support the feasibility of additively manufactured PLA-based umbrella wheels as geometrically adaptive locomotion components for stair-climbing robots. The observed stress patterns provide a useful basis for future design refinement, material selection, and more comprehensive experimental validation.

CONCLUSION

This paper described the design, additive manufacturing and the performance analysis of an FDM printed PLA based umbrella wheel mechanism to be utilized in stair-climbing robots. Four-segment umbrella wheel geometry was designed, and the kinematic behaviour was mathematically modeled and compared to the results of ADAMS multibody simulation with similar motion trends and transformation between rolling and step climbing configuration. ANSYS structural finite element analysis revealed that the greatest stresses are primarily at the long-short arm junction and around the curved rim segments. At a combined robot and payload mass of 20 kg, von Mises maxima was around 48-50 MPa, which is still within the permissible strength range of FDM-printed PLA to operate it as a moderate-load proof-of-concept.

Comparatively, the proposed umbrella wheel can be considered an intermediate technology between traditional and wheeled devices, and more intricate tracked devices or wheel-leg stair-climbing systems. Its key benefits include lower mechanical complexity and weight, and the ability to roll efficiently on flat surfaces and continue to provide more support stability and terrain flexibility in the process of stair climbing. Testing of a prototype that was 3D-printed showed that the expansion and contraction of the wheel was stable, that 7 cm steps could be climbed with the expansion wheel of diameter 14 cm, and that the wheel could be operated.

The current paper also notes some significant drawbacks of FDM-fabricated PLA components, such as fatigue and wear in repeated stair-contact cycles, anisotropy due to layer-wise fabrication, and sensitivity of the structural response to material property and printing conditions, such as raster orientation, infill density, and interlayer bonding quality. Moreover, even though the mechanism can be scaled in principle, its response to a variety of robot sizes, as well as to a variety of real-world stair geometries, will necessitate a coordinated redesign of geometry, material choice, and actuator capacity, and then multi-geometry experimental validation. In general, the existing findings validate the possibility of the proposed umbrella wheel as a lightweight and geometrical adaptive proof-of-concept of stair-climbing robots. Future research ought to be directed towards quantitative hardware testing, cyclic reliability testing, parametric sensitivity analysis, supported filament options, and scaling to real-world applications.

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