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Design and Optimization of Transformer Robot for Transformation of Wheel to Leg Track Wheel

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Abstract

A legged wheel transformable robot is a type of robot that can transform its wheel in complex situations and regain its original shape. Those robots can be used for indoor services like cleaning, delivery, and healthcare as well as in the fields of agriculture, logistics supply, and space exploration. But ordinary wheels cannot overcome complex shapes and situations like climbing up flat or spiral stairs, traversing various terrains, and obstacles as they face problems of misstep, slipping, and misalignment. So, a legged wheel hybrid transformable robot can be a solution because it can transform its wheels to overcome complex shapes and situations. Flexibility, adaptability, and stability of the robot can be achieved by implementing different mechanisms. In this paper fold and spread mechanism is used and a wheel is developed which has 2 degrees of freedom (DOF). In this paper, the detailed design of the wheel and transformer robot, the measurement of torque, and the transformation mechanism are discussed.

Keywords: legged wheel, torque, transformation.

1. Introduction

Stair climbing is one of the challenging parts for indoor service robots. In The DARPA Robotics Challenge (DRC) program,2015 the eight tasks (Drive, Egress, Door, Valve, Wall, Surprise, Rubble, and Stairs) were performed and 30% of all robots could not complete the stair climbing challenge [1]. Stair climbing is very difficult as the height and length of stairs are different for different countries and different purposes according to the International Building Code (IBC). Material, geometry, the environment surrounding the stairs, shape, size, and location of stairs make an impression on stair climbing ability and performance. The dynamic condition of the stair provides important information about the kinematic analysis, static analysis of friction coefficient, torque, mechanism, wheel radius, and length of link[2]. The shape and size of stairs also create some problems Some types of robots stuck in the nose of a stair during stair climbing[3], cannot obtain enough friction[4]. Again the radius of a wheel also creates an impact on stair climbing ability[5]. For climbing up stairs different mechanisms are being used such as the morphing mechanism[6],5 bar PRRRP mechanism[7], foldable rim-based transition mechanism[8], and others. According to the locomotion method, the robotic platforms can be classified into four categories: tracked, legged, wheel-legged, and wheel-linkage robots. A tracked robot uses a very simple method and is less susceptible to the size of stairs but it finds difficulty in climbing when a huge nose of stairs is present for example a trackedtype crawler robot is a simple type of robot which have one single body. Those types of robots use active swing idler mechanisms [9] and have the ability to carry heavy loads too. sometimes more than two flippers are used in mobile tracked type robots to increase friction and contact area and help the robot to climb up stairs nose more effectively. Those flippers help to change the shape. That robot shows some complex interaction with stairs [10]. Multibody robot is also another type of tracked robot which consists of two or more modules. RAPOSA is a tracked robot that has tracked wheels and can allow upside-down motion [11], Amoeba-2 shows both parallel and linear configuration [12]. A legged robot is mainly inspired by humans or time animals. Those need a complex control system to control with a more degree of freedoms (DOFs). Those can be different types like two-legged robots with torque control methods, have a wide range of walking speeds [13], inverse kinematics, and inverse dynamics for controlling methods [14]. For controlling a robot frequently more degree of freedom is needed. Some two-legged robots have more than 10 (DOFs). For example, HRP-4 is a humanoid robot of 34 DOF [15]and ASIMO is a bipedal robot of 28 DOF [16]. But a huge problem of a two-legged robot is its balancing ability. A four-legged robot has easy balancing ability and carrying load's ability [17]. Some robot-like Boston Dynamics spot robots have next-generation mobility systems with "NeBula" architecture [18], four-legged robots that have low impedance transmission, and energy regenerative electronics [19]. A six-legged robot has more balancing

ability [20]. A wheel linkage robot is useful for uneven surfaces and can effectively climb up and down various sizes of stairs. These types of robots contain both wheels and linkage connecting with the main body. An example of a wheel linkage robot is a rocker bogie-based robot. This robot uses the Taguchi method because of its simplicity [21]. Wheelchairs [22] and multi-wheel linkage robots [23] are also common examples of wheel-linkage robots. A wheel-legged robot is a type of robot that can transform a wheel into a leg at the time of climbing the stairs. Different types of transforming mechanisms are being used. For example, leg-type wheel-based robots; have spoken base design. ASGUARD is a type of robot that can deal with rubble, gravel, and stairs but has high energy consumption due to friction [24]. "TurboQuad" is a wheel leg transformable robot that works on a novel mechanism that allows it to transform its morphology without hampering its movement. Wheeled mode, legged trot mode, and legged walk mode are three common modes of "TurboQuad"[25], [26]and star wheel-based robots are the most common examples of wheel-legged robots [27], [28].
This paper mainly focuses on wheel-legged transformer-type robots. The paper is organized as follows: section 2 describes the mechanical structure of the robot Section 3 describes the transformable wheel mechanism along with wheel design. Section 4 highlights the general procedure for obstacle climbing and required torque calculation for spreading the wheel and section 5 contains the discussion and overall conclusion part.

2. Mechanical structure

The robot can climb up stairs by transforming its wheels. The wheels are usually round and at the time of climbing stairs, the shape changes into a star-like structure or four-bladed fan shape. The robot is three-wheeled. The two wheels located at the front of the structure can transform and the third wheel located at the back is present for support. Fig. 1. shows the mechanical structure of the setup. The third wheel is a cluster wheel and it helps to support the structure. The cluster wheel can move in multiple directions. The body of the robot is made of PVC board. The length of the setup is 23 cm. The width is 17.5 cm. Two L-shaped arms are present at the front side of the setup. So, the total width in the front is 33 cm. Two types of motors are being used in the robot. For simple, rotation of the wheel and liner movement a pair of geared DC motors are used. Those DC motors are the combination of gearbox and electric motor and help the system to move forward and backward. A SG 90 Micro Servo Motor is present for transforming the wheel. The outer L-shaped arm of the structure holds the servo motor. A motor driver module (L298) is used to operate the two DC motors. It also controls the velocity of the robot. All the elements are attached to Arduino Uno SMD R3 with ATmega328P MCU for control purposes. For the power system, two lithium-ion (Li-ion) batteries are used of 3.7v and 1000-1200mAh.The overall weight of the robot is 0.5 kg and very light in weight and easy to handle.

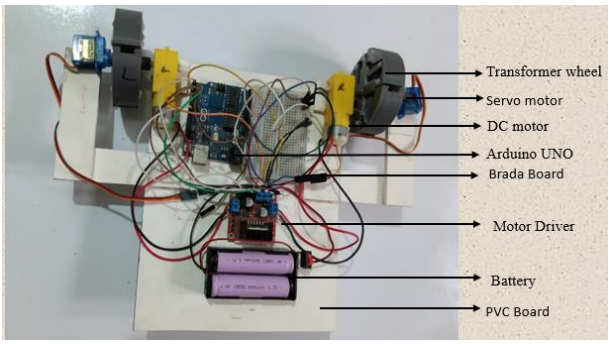


Fig. 1. Mechanical structure of the setup

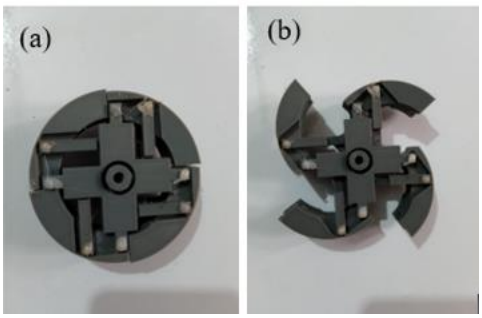


Fig. 2. Transformation of wheel (a) circular shape (b) legged shaped

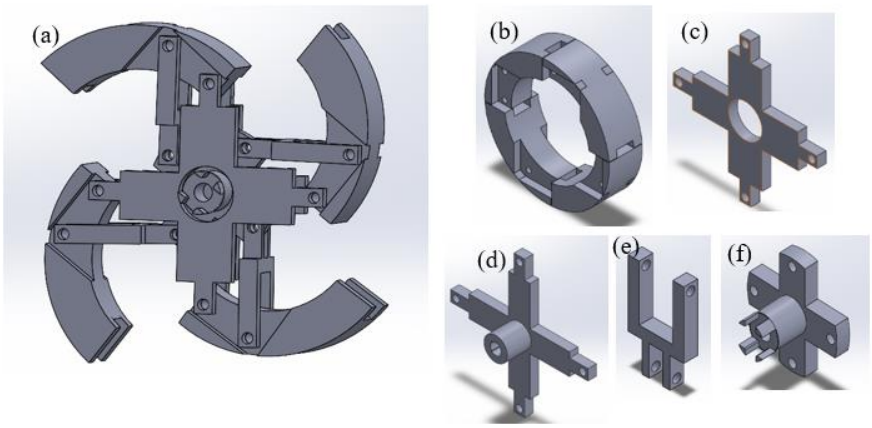


Fig. 3. Transforming Wheel (a) wheel spread state and elements of the wheel (b) outer ring (c) thick holder (d) thin holder (e) inner linkage (f) rotor.

3. Wheel design and mechanism

The wheels used in this robot are designed in SolidWorks software and manufactured by 3D printing. The wheel design is simple and easy to control. Fig.2. shows the wheel. In Fig. 2(a) the wheel is in its original shape and in Fig. 2(b) the wheel is in its transforming shape. The wheel has 5 main parts and those combine into a single wheel. Fig. 3 shows the elements of the wheel. The outer circular surface is called the outer ring. The outer ring is the main structure of the wheel. It is cut into 4 pieces. These pieces are separated from each other. A small 0.01 cm gap is present between each pair of pieces. The outer diameter of the wheel is 7.50 cm and the thickness is 1.2 cm. For better gripping purposes each piece has square shaped hole at the end. The next important part is the inner arm connector which is called the inner linkage. A complete wheel requires 4 inner linkages. These connect the outer ring with the inner rotating part. The inner linkages are in U-shaped. The main purpose of this part is to convert the rotational motion into linear motion so that the wheel can transform its shape into a star-like structure. The length of this connector is 3.45 cm. Inside the outer ring, an inner ring is present called the rotor. It is the most important part because the shape of the wheel changes by rotating this part. A small shaft is placed at the center of the rotor for gripping and rotating purposes. This small shaft has a small hole that holds the servo motor. The last two parts of the wheel are the thick holder and the thin holder. Each has four arms. The thick holder has a hole in its center and the shaft of the rotor comes out from this hole and the thin holder has a small shaft in its center which holds an arm of the DC motor. The wheel works on a fold-and-spread mechanism. When the rotor rotates with the help of a servo motor then the outer ring spreads and forms a four-legged wheel. Again, when the servo motor rotates in a reverse direction the four legs are folded back and formed into a circular shape.

4. General procedure for obstacle climbing

Step 1: Detecting the obstacle and stop the rotating DC motor: Detecting an obstacle is the first step. Usually, the wheel of the robot is circular and shows linear movement in forward and backward directions. The forward and backward movements are controlled by the DC motor and the motor driver. Detecting obstacles can be done in different ways. Using a camera, a motion sensor or detection by a controller is the most common. In this setup, the obstacles are detected manually by the controller. After detecting the obstacles, the DC motor controlled by the motor driver is stopped. The distance between the obstacle and the outer ring of the wheel becomes zero. This means when the wheels touch the obstacle the DC motor stops.

Step 2: Transformation of the wheels: When the linear motion of the wheel is stopped then the transformation of the wheel starts. The transformation of the wheel is operated by the servo motor controlled by the Arduino Uno. The rotation angle of around 40 to 50 degrees of the rotor is needed for the transformation of the wheels. The Servo motor rotates the rotor which spreads the outer ring of the wheel and the circular wheel transforms into a four-legged wheel. After the transformation, the radius of the wheel increases about 2 times. Now it can easily overcome the obstacle. The servo motor needs to stop its work to hold the shape after transformation.

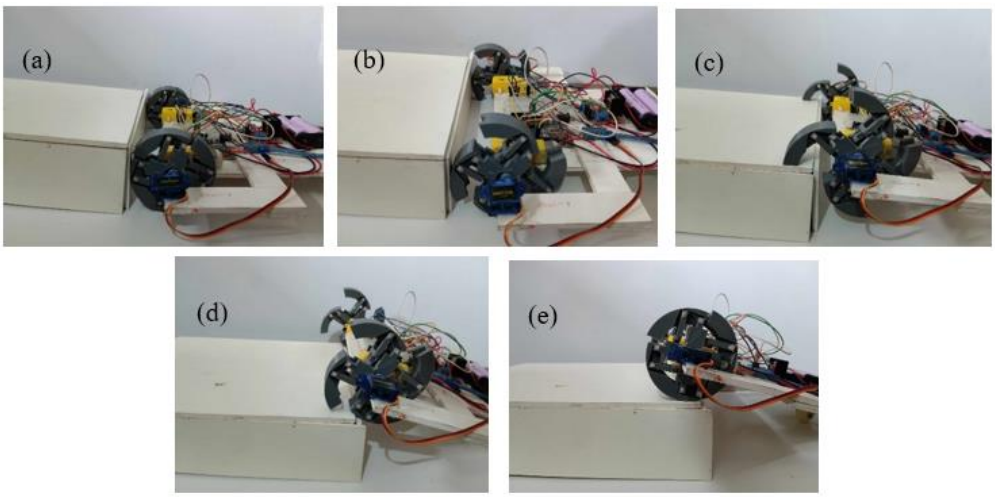


Fig. 4. Process for obstacle climbing (a) detecting obstacle and stopping rotating DC motor (b) transformation of Wheels (c) climbing up obstacle (d) climbing top of the obstacle (e) regaining original form

Step 3: climbing the obstacle: For climbing up an obstacle first thing needed is to start rotating the DC motor. The DC motor helps to rotate the whole wheel as the shaft of the wheel is connected to the holder which is attached to the outer ring. As the size of the wheel increases so, the torque also increases. The leg of the wheel then creates uplift force and the wheel starts to climb up the obstacles.
Step 4: climb to the top of the obstacle: continuously rotating of DC motor helps to overcome the obstacle. The wheel stays up at the top of the obstacle.
Step 5: Back to its original shape: When the tip of the obstacle is overcome, the DC motor stops rotating and the servo motor rotates in an anti-clock direction about 40 to 50 degrees to regain its circular shape.
All those processes are repeated for climbing any stair. Fig.4 shows all the sequential processes of climbing up any object or one single step of the stairs.

Torque calculation

For the wheel two types of conditions; static and dynamic conditions are present. For static condition, the linear acceleration along in the direction of x is zero ($a_x = 0$) but for dynamic condition a_x is available. Equation 1 shows the condition for static and dynamic motion. For rotating it requires the necessary torque to spread the arms. Fig. 5(a) shows the dynamic condition when the wheel rotates and stops and Fig. 5(b) shows the forces acting on a wheel when it begins to transform. Forces are acting on joints.

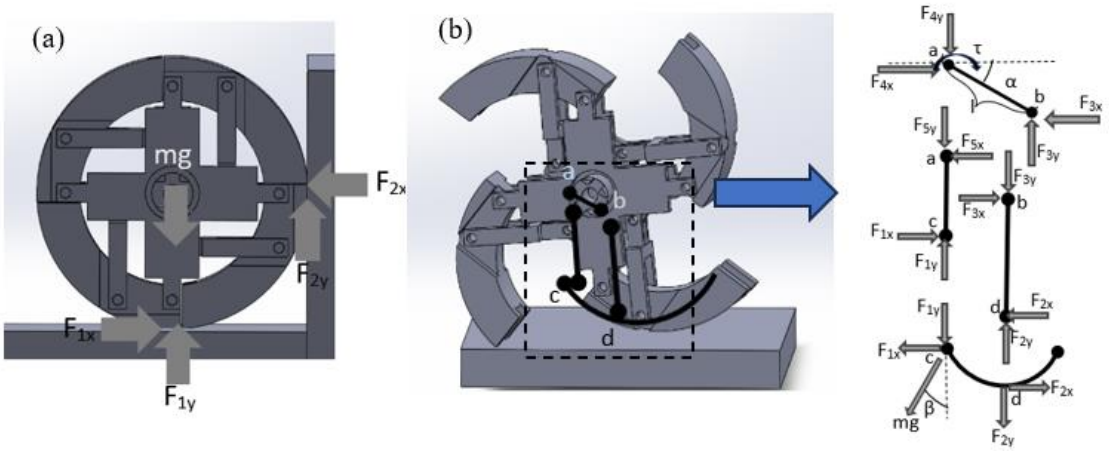


Fig.5. Free body diagram of (a) wheel at dynamic condition (b) wheel at transforming condition while forces acting on all joints

Equations for the wheel while staying at its original shape are:

$$F_{1x} - F_{2x} = ma_x \quad (1)$$

$$F_{1y} - F_{2y} - mg = ma_y \quad (2)$$

Equations when the wheel is in transformed condition are:

In the direction of X: $\sum F_x = 0$; So, equation:

$$F_{3x}\cos\alpha - F_{4x} = 0 \quad (3)$$

$$F_{5x} - F_{1x} = 0 \quad (4)$$

$$F_{1x} - F_{2x} - mg\sin\beta = 0 \quad (5)$$

$$F_{2x} - F_{3x} = 0 \quad (6)$$

In the direction of Y: $\sum F_y = 0$; so, equation

$$F_{4y} - F_{3x}\sin\alpha = 0 \quad (7)$$

$$F_{5y} - F_{1y} = 0 \quad (8)$$

$$F_{1y} + F_{2y} + mg\cos\beta = 0 \quad (9)$$

$$F_{2y} - F_{3y} = 0 \quad (10)$$

So required Torque to operate:

$$\tau + F_{3x}\cos\alpha \times l - F_{3y}\sin\alpha \times l = 0 \quad (11)$$

$$\tau = F_{3y}\sin\alpha \times l - F_{3x}\cos\alpha \times l \quad (12)$$

Solving equation (12) will provide the necessary torque for spreading the wheel from the wheel to a legged shape. The value of F_{3y} and F_{3x} can be achieved by solving the equation (3) to equation (6) and from equation (7) to equation (10). Values of those forces and angles are variable and can change concerning the position of wheel.

6. Discussion and Conclusion

The transformation of a wheel from a circular shape to a legged shape increases the ability to withstand the situation of object climbing as well as climbing up stairs. Maintaining balance and opening the face of a wheel at the right time to transform are the main challenges. The height of the object that needs to be overcome is related to the radius of the wheel. If the radius of the wheel increases, then it can overcome larger objects. Again, the speed of rotation of the wheel by the main DC motor can be changed by changing the Arduino Uno code. The speed of the wheel needs to change if the obstacle's size and shape change. Further development can be done by changing the wheel surface from smooth to rough so that the wheel can withstand into slipper surface and better griping can be achieved.

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