Design of a wheel legged robot*

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Abstract
The design and development of a robot capable of climbing stairs and moving on uneven terrains represents a significant advancement in the field of robotics, particularly in applications where adaptability in challenging environments is crucial. This type of robot becomes an invaluable tool in a variety of scenarios, from search and rescue operations in disaster-affected areas to exploration tasks in unknown or inaccessible terrains for humans. What sets this robot apart is its efficient rotational capacity across various surfaces. This capability not only allows it to navigate obstacles more effectively but also enhances its practical utility when faced with varied and difficult terrains. Its ability to adapt to different types of surfaces, whether smooth, rough, inclined, or irregular, makes it extremely versatile and suitable for a wide range of applications. Furthermore, the efficiency in the robot's rotational capacity not only enhances its mobility but can also have significant implications in terms of energy consumption and durability. An optimized rotation system can reduce the load on the robot's components and prolong its lifespan, making it a more sustainable and economically viable long-term solution.

Keywords 1
Climbing stairs, Uneven terrains, adaptability, rotational capacity

1. Introduction

The design of intelligent mobile robots capable of smoothly moving and walking on stepped terrains is an important research topic in this field. Currently, intelligent mobile robots designed for various operational environments and terrains primarily utilize mobile structures such as wheels, tracks, feet, links, etc. Numerous scholars have developed different approaches for stair climbing based on various modes of movement [1]. Mobile robots have been successfully developed in various sizes and customized for specific robotic applications. In the field of rescue operations, these robots bring significant advantages, such as minimizing personnel needs, alleviating fatigue, and enabling access to previously unreachable areas [2].

Stairs represent common challenges in indoor environments and are complicated for robots to overcome. The climbing speed of robots on stairs, especially for commercial applications, is intended to be comparable to that of humans, although still limited. Additionally, the diversity in stair dimensions presents a significant challenge [3]. The unique shape and small turning radius of spiral stairs pose a major challenge for tracked vehicles. When ascending, robots encounter difficulties in making inward turns on the staircase due to the irregularity of the terrain, causing the left or right track to slip during rotation [4]. Indoors, there is a wide range of stairs in terms of shapes and sizes, as well as a variety of materials ranging from wood to metal and concrete, which cater to different applications and architectural styles. The geometry of stairs also varies, from conventional straight designs to more complex shapes [5].

To streamline the stair climbing process, it is possible to improve the forward movement stability of the vehicle by increasing its speed. Additionally, the speed and flexibility of the leg's initial movement can be optimized, and the staircase can be identified using distance sensors [6]. The trajectory optimization scheme implemented confirmed the effectiveness of scenarios related to climbing stairs and moving upright. For solving other cases, a new open-source implementation is provided that can be directly integrated into our motion planning software, but unlike the previous use of contact force

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[7]. Developing and analyzing an innovative robot with the ability to ascend spiral stairs, equipped with the capability to turn and move on uneven terrains. The main objective is to enhance the adaptability of robots to challenging environments and provide an effective solution for mobility in urban and rural areas where the topography is irregular. Faced with the many problems and difficulties that a robot may encounter when mobilizing, it was decided to develop a robot that is as optimized as possible so that these obstacles no longer pose a problem. Through the development of this versatile robot capable of effectively and safely overcoming these obstacles, this study aims to drive advancements in mobile robotics technology and promote its practical utility in real-world situations.

2. State of art

Based on locomotion variation, robots designed for climbing stairs can be classified into crawler robots, wheeled robots, legged robots, and hybrid robots, with the increasing popularity of modular and reconfigurable robots, more attention is being paid to mechanical design [8]. To avoid locking problems caused by friction between joints and stairs, a different approach is adopted, which consists of reducing the number of joints along the robot's body while increasing the proportion of segments responsible for generating propulsive forces, each section of the flexible caterpillar [9]. One of its outstanding characteristics lies in consolidating various functions into a single robot, this singularity is evident in the use of a shared power source and transmission system, creating an extraordinary opportunity to examine performance variability using the same inputs [10].

Although these sliding movements are ignored, perfect static alignment between the motorized and anatomical axes is not achievable, as the anatomical axis cannot be precisely located when using the motorized exoskeleton, ultimately, even an initially optimally aligned exoskeleton can lose its alignment due to compression [11].

There are two categories of robots designed to assist the elderly in mobility, known as cane-type robots and bipedal robots, and both utilize the handrail as support during walking and stair climbing, with the former employing tires and rubber belts, while the latter uses two legs to facilitate movement [12]. Smaller robots often adopt the strategy of "jumping" from one step to another when climbing stairs, for example, the Scout employs a small tail, usually designed to maintain balance, to perform autonomous jumps on a flight of stairs, likewise, robots with smaller legs [13]. Typical modes of locomotion in these ground robots include the use of wheels, legs, and tracks, with wheels enabling simple and effective locomotion on relatively smooth and flat surfaces, although they present restrictions when faced with rough terrain or obstacles [14]. The stair-climbing robot serves as an innovative transportation mode that provides electrical assistance to the user, its operation relies heavily on its design and calculations, including the use of tri-star wheels as a variant to the design for climbing stairs and a load sensor in the handle to control the electric motors [15].

It is also possible to climb stairs with a two-wheeled robot as a flipping mechanism is developed, raising one wheel and rotating the other on its own axis, also known as the dynamics of the model and control system for two-wheel balancing [16]. The development and control of a mobile robot capable of navigating narrow spaces, three-dimensional terrains, and scaling steep stairs represent significant advancements. Two innovative control methods are presented: one focused on three-dimensional direction, allowing the robot to adapt to the surrounding terrain by relaxing its joints and using its own weight to follow the topography [17].

A framework has been developed for stair climbing by a quadruped robot, with a primary focus on fall prevention during the ascent process. To achieve this purpose, this framework employs the zero-moment point (ZMP) based on direct force to plan the movement of the center of mass and control the landing force [18].

Also, in the field of human health, robotics is present with the development of a prototype electric wheelchair capable of elevating itself and overcoming obstacles, such as stairs. This represents an exciting advancement in mobility technology. The design and creation process of this wheelchair has been an impressive technical challenge [19]. The introduction of an innovative system with a tracked wheelchair design to facilitate stair ascent comprises a main chassis and rubber-tracked arms that offer support, being adaptable to various types of stairs. Additionally, the design of the control system necessary for the wheelchair operation when ascending or descending steps is addressed [20]. The launch of a new real-time control framework is a crucial evolution to enhance the adaptability and resilience of quadruped robots in challenging terrains. This innovative method omits distance measurements or visual sensors for terrain mapping and has the capacity to manage various contact surfaces with notable differences between them [21]. The importance of improving the performance of mobile robots in irregular terrains and overcoming the limitations of robots with wheels or tracks is also highlighted. Additionally, the design and implementation of an involute curve mechanism for stair climbing by a mobile robot are described, presenting a kinematic model for stair climbing movement using the involute curve [22].

The objective is to develop a robot capable of autonomously and stably climbing different stair structures in various scenarios. The robot uses a four-step climbing motion pattern: "approach, elevation, placement, and retraction". Relevant kinematic and dynamic models are established to study the robot's constraint relationship [23]. To improve climbing capability and safety of vehicles used for transporting people and heavy loads in environments with stairs, the article classifies climbing vehicles according to their load capacity and mode of locomotion. Different types of climbing platforms are detailed, such as those based on tracks, wheeled systems, articulated mechanisms, hybrid variants, and those that combine legs and wheels [24]. Designs of robots specialized in stair climbing represent a combination of engineering and technology, where the integration of advanced traction systems and structural calculations demonstrate the versatility of robotics in facing complex challenges in daily environments [25].

It is also possible to climb stairs with a two-wheeled robot since a flipping mechanism is developed, raising one wheel and rotating the other on its own axis, also known as the model dynamics and control system for two-wheel balancing [26]. As it is known in the industry, there are endless scenarios that can test these devices, and stairs are no exception. This evolution has radically transformed the landscape of robot mobility, not only improving their ability to overcome vertical obstacles [27]. An innovative mechanism of active rotating legs for stair-climbing mobility vehicles is presented, highlighting its compact and lightweight design that reduces the necessary torque. Design principles are addressed [28]. This study analyzes the biomechanics in the sagittal plane of the lower limb joints during stair climbing, considering three specific walking speeds: 0.35 m/s, 0.5 m/s, and 0.65 m/s [29]. This study addresses the application of mobile robotics in various fields such as agriculture, surveillance, rehabilitation, space exploration, and logistics, focusing on the hybrid design of wheels with legs to overcome complex obstacles, especially stairs, through dynamic simulations. The research analyzes how the geometry of the wheeled legs affects the robot's performance when climbing stairs, highlighting the leg opening as a crucial parameter [30].

A new solution is presented for a robotic exoskeleton system used in locomotor assistance for people with motor disabilities, proposing a novel structural solution of a flat parallel kinematic chain to be used as a leg for an exoskeleton [31].

3. Methods

Designing and developing a robot capable of overcoming stairs and navigating uneven terrain, with the additional ability to perform smooth turns as shown in Figure 1. It aims to enhance mobility in complex environments, providing practical solutions for common challenges across various fields of application. The main focus lies in creating a versatile and robust locomotion system that enables the robot to dynamically adapt to its surroundings, ensuring safe and efficient movement in variable conditions, including the ability to overcome stairs of any type, including spiral stairs, thanks to its optimal turning capability.

With the wheels ready, our second challenge was the chassis, based on the Waltr structure with PLA wall chassis and carbon fiber frame [33], to make it lightweight and reduce necessary torque. In our case, we replaced carbon fiber with aluminum angles.

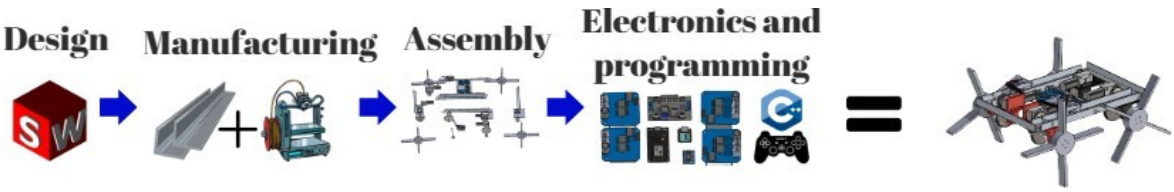

Figure 1 integrative image

The method followed to design and manufacture this robot firstly required the ability to climb stairs and navigate uneven terrain, and we decided to apply the calculations for Wheel-legged design for stair climbing given by [32].

The C_mor constant with a value of 1.3 was used because it falls within the range of measurements necessary to overcome the stairs. To calculate the value of the O_N aperture, the constant C_mor and the length of the ladder diagonal were used l_d, starting from (1).

$$O_N = C_{mor} * l_d \quad (1)$$

To obtain l_d, the measurements of the steps, both the width l_w and the height l_h, are used, and it is calculated from (2).

$$l_d = \sqrt{l_w^2 + l_h^2} \quad (2)$$

The geometry of the wheel is determined by the number of blades N_i it will be composed of. With this, we can obtain the angle θ, which will be the separation between blades, and it is calculated using (3).

$$\theta = \frac{360}{N_i} \quad (3)$$

With most calculations already performed, we have now obtained the wheel diameter using

(4). $$w_d = \frac{O_N}{\sin\left(\frac{\theta}{2}\right)} \quad (4)$$

With the wheel diameter already calculated, we obtained the radius w_r, which is fundamental for
calculating the distance between centers c_w given by (5).

$$c_w = c_{e1} + 0.75\, w_r \quad (5)$$

And other equations for the structure are obtained through (6), (7) and (8).

$$c_{e1}^2 = w_r^2 + d_e^2 - 2(w_r)(d_e)\cos\varnothing \quad (6)$$

$$d_e = \sqrt{(1.5\, l_w)^2 + (2\, l_h)^2} \quad (7)$$

$$\varnothing = 89 - \tan^{-1}\frac{2\, l_h}{1.5\, l_w} \quad (8)$$

Taking into account all the necessary calculations to obtain the physical prototype of the robot, we decided to implement gears to increase the torque and consequently decrease the speed since the O_N aperture is very large. We decided to have 4 leg blades, which would require a very high torque. Now, Choosing a module of 2 for both gears, we can determine our pitch diameters (9).

$$D = m \times N \qquad (10)$$
$$D_1 = 2\,x\,20 = 40$$
$$D_2 = 2\,x\,40 = 80$$

So, the torque ratio would be (10):

$$\frac{T_1}{T_2} = \frac{D_2}{D_1} = \frac{80}{40} = 2$$

This means that the torque on gear 1 is twice the torque on gear 2. Having motors of 100 kg·cm, we will double the torque to 200 kg·cm.

Taking into account the H-bridges:

Given that the nominal force of your motor is 200 kg·cm, we need to calculate the new torque by multiplying this value by the percentage of PWM used (11).

$$new\ torque = \frac{190}{255}\,x\,200 = 149.02\,kg.cm \qquad (11)$$

Now we obtain the speed at which our shaft will rotate, we have a motor with a speed of 160 RPM, but we have an H-bridge to regulate the motor speed through PWM (0-255), sending it a pulse width modulation of 190 (12).

$$Motor\ speed = \frac{128}{255}\,x\,160 = 80.31\,rmp \qquad (12)$$

Taking this into account, we can now begin to calculate the speed at which our wheels will rotate using the speed ratio between the gears (13).

$$V_2 = \frac{75}{2} = 37.5\,rpm \qquad (13)$$

For the creation of the robot, computer-aided design (CAD) using SolidWorks was employed. During the manufacturing process, additive manufacturing was opted for using PLA, along with metal angles, resulting in a lightweight and durable structure.

We faced the challenge of overcoming a spiral staircase (with an intermediate landing), with a height of 9cm x 15cm wide. Therefore, our initial challenge was to rotate the robot as it had to climb the stairs and turn at the "STAIRWAY REST" to continue overcoming the other part of these stairs as shown in Figure 2. Considering the height of the steps obtained as the target to be able to climb them, the necessary measurements to overcome each step were identified [32]. Three respective simulations were conducted with the measurements of each step: lh 9 lw 15, conducting a simulation on a structure similar to the spiral step with an intermediate landing between both parts. The different simulations were performed with initial weight differences; initially, we used 30 lbf, increasing by 10 lbf in each simulation to observe the movement differences until reaching 50 lbf. All simulations were conducted at 40 rpm.

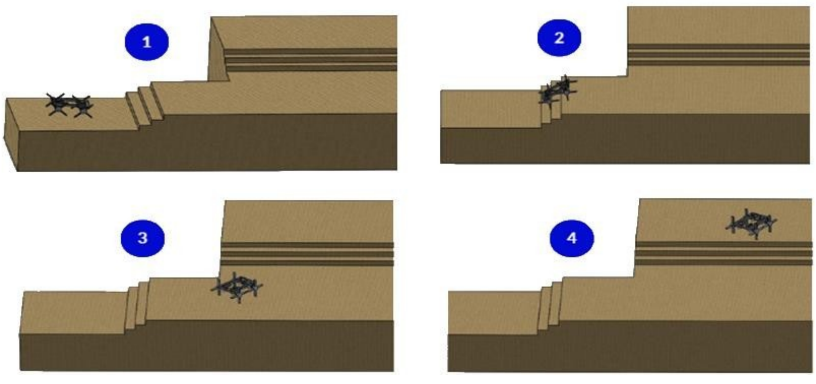

Figure 2 climbing sequence

4. Results

The designed robot has the unique ability to ascend stairways with landings, enabling it to overcome obstacles with greater efficiency and safety. Additionally, its capability to rotate provides it with additional versatility, allowing it to navigate obstacles smoothly and dynamically adapt to changing environments. This innovative approach, combining stair climbing with landings and rotational capability, gives the robot a significant advantage in terms of mobility and adaptability, making it an invaluable tool in a variety of applications, ranging from rescue operations to exploration of challenging terrains. In figure 3, it can be observed that when the robot starts to rotate, the center of mass shifts due to the redistribution of weight and the inertia generated by the turning motion. Rotational motion involves changes in the direction of motion, which creates inertia. Paddle legs have mass and moving them in a rotation will require more effort due to the inherent resistance to changing their direction of motion.

When changing direction or moving up or down levels, the inertia of the system also changes. and changes in inertia can affect the angular speed of the motor.

Navigating through irregular terrains and climbing stairs with a robot that utilizes paddle-style wheels has shown positive results in various aspects. Firstly, the design of paddle-style wheels provides exceptional traction on a variety of surfaces, allowing the robot to remain stable and move effectively even on challenging terrains. The arrangement of four paddles per wheel evenly distributes the load and maximizes the ground contact area, enhancing the robot's capability to overcome obstacles and prevent slipping

Moreover, using this type of wheels enables the robot to navigate stairs with greater ease and safety. The paddles offer a firm grip on each step, minimizing the risk of slips or falls during ascent or descent.

This ability to successfully tackle vertical obstacles significantly expands the robot's reach and usefulness in various environments, from urban settings to industrial applications.

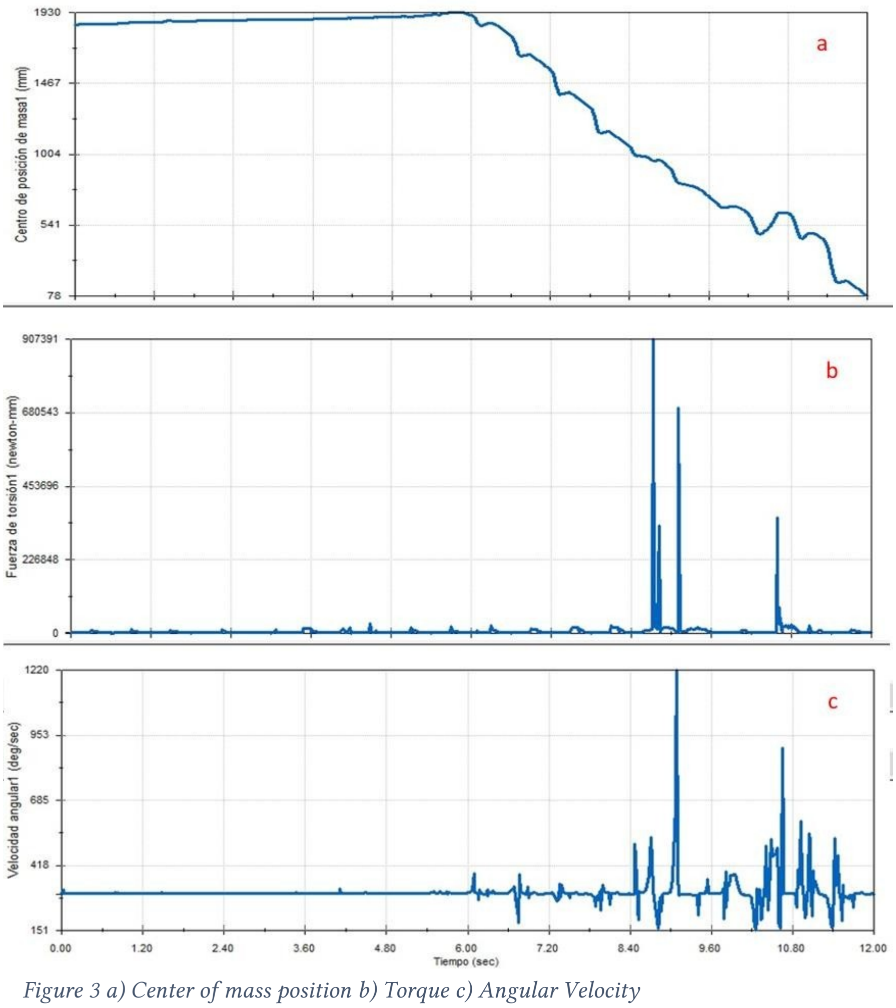

Figure 3 a) Center of mass position b) Torque c) Angular Velocity

The positive results obtained from navigating irregular terrains and climbing stairs with this type of robot not only improve operational efficiency but also have significant implications for safety and accessibility. By providing a robust and reliable solution for mobility in challenging environments, this technology can have a significant impact across a wide range of applications, from space exploration to assisting in daily tasks for people with reduced mobility.

During the rigorous process of testing and evaluation, a significant opportunity to improve the robot's performance was highlighted. It became evident that the wheels, made from PLA material using 3D printing technology, could induce instability due to vibrations caused by the dynamic interaction between the ground and the material. This critical observation underscored the importance of proactively addressing this challenge to optimize the robot's performance under various operational conditions.

To tackle this challenge, a solution was implemented by incorporating a three-axis gyroscope and accelerometer sensor, specifically the MPU6050. This device was integrated with the purpose of accurately measuring the vibrations generated as the robot moves over uneven terrain. The addition of this sensor provided detailed and relevant data regarding the robot's motion dynamics.

The accelerometer integrated into the MPU6050 sensor provides measurements of linear acceleration in three axes (x, y, z), typically expressed in units of gravity (g), This allows the sensor to detect changes in the object's velocity of movement in different directions Figure 4 and Figure 5.

Figure 4 measurement with PLA

We opted for an innovative solution by incorporating a part manufactured through 3D printing using a type of material known as TPU (thermoplastic polyurethane). TPU is a flexible and durable elastomeric material that offers excellent impact and vibration absorption capabilities. By adding these TPU parts to the robot's design, we were able to effectively counteract the vibrations generated during its operation on uneven terrain.

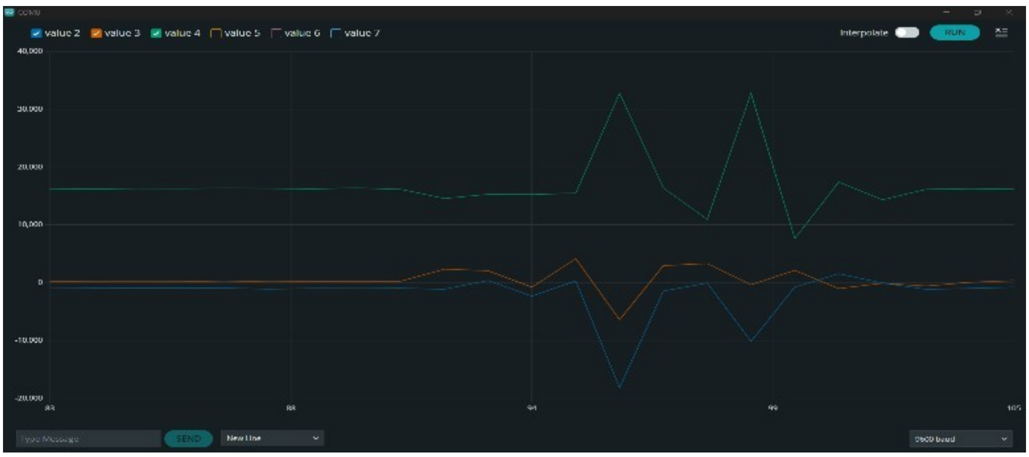

Figure 5 measurement with TPU

5. Discussion

In comparison to classic robots that move linearly and may face limitations in their ability to navigate obstacles and adapt to sudden changes in the environment, which can affect their effectiveness and performance in challenging situations such as stair climbing. A stair-climbing robot equipped with a steering system for turning provides a notable advantage in terms of maneuverability and versatility. This type of system allows the robot to adapt more efficiently to complex environments and change direction as needed, increasing its ability to navigate obstacles and effectively maneuver in confined spaces. A protection was designed and fabricated for the legs of each wheel, and the material used for these is TPU. Thanks to this, we were able to make a series of comparisons of how the robot behaved when it had these protections on each of its legs and when it did not. With the help of an MPU4060 gyroscope sensor, we were able to capture graphically how vibrations affect the entire robot. This is where the TPU protections play a very important role, as they greatly reduce all vibrations that occur when the robot is in motion.

6. Conclusion

The study proposes several technical approaches to overcome mobility issues on stairs. From tracked robots to innovative designs of planetary gears, each approach offers specific solutions tailored to different environments. Adaptability and versatility are key aspects of designing a climbing robot. The ability to accommodate stairs of various sizes, shapes, and materials, including complex curved stairs, emphasizes the importance of versatile equipment that can effectively operate in a variety of environments.

Figure 6 shows the prototype, it is important to use criteria such as power, speed, energy efficiency, and terrain negotiation abilities to evaluate and compare the robot's performance. This comprehensive assessment provides a complete overview of the capabilities and limitations of each design. The ability of some robots to reconfigure is considered an innovative strategy to adapt to environmental changes. This approach not only solves mobility issues but also provides greater fault tolerance and enhances device durability. The implementation of open-source trajectory optimization, using variables such as center of mass acceleration and angular momentum, was identified to significantly contribute to improving the range and effectiveness of the robot in scenarios involving different movements.

Figure 6 physical prototype

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