Eötvös Loránd University

Pattern Morphing Tire & Topography Adaptivity AMAT

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Abstract

Our advancement of mobility technologies for automobiles and other fields such as space exploration requires us to modernize and reinvent technologies that have lagged over the years. One of those technologies involves the reintroduction and modernization of tires. Traditionally, pneumatic tires, though widely used, suffer from many well-known limitations such as vulnerability to punctures, terrain-specific inefficiency, and localized wear and tears due to concentrated load points. These issues are particularly critical for safety and long-term durability, often contributing to accidents, insufficient grip in wet conditions, and overall reduced performance.

The **Adaptive Morphing Airless Tire (AMAT)** technology addresses these challenges and is designed to be a forward-compatible solution for the next generation of electric and autonomous vehicles. This proposal presents an innovative answer to the long-standing limitations of traditional tires: a fully airless system using gyroid-based internal lattice structures that provide elasticity, structural resilience, and shock absorption, combined with servo-actuated, terrain-responsive outer treads capable of adapting in real time to environmental conditions. This allows for enhanced grip, stability, and durability across diverse surfaces.

The design includes triply periodic minimal surface (TPMS) geometries, for our situation a gyroid lattice structure which offers a much greater shock absorption spectrum and even for stress distribution, including the excellent structural integrity without the need for inflation or any type of pressure-force being exerted back onto the inner tire wall. The outer layer of the tire is a modular morphable tread segment that responds to dynamic terrain conditions using input devices and machine-based learning system from onboard sensors such as LiDAR and visual recognition. This enables the tire to adjust its grip profile in real-time for optimal performance across a wide range of surfaces, from urban roads to rugged off-road trails.

The defining and main strength of this innovation falls on its widespread compatibility with existing vehicle architecture. The AMAT Tire can fit any type of standard wheel dimensions, hub connections, and axle interfaces, allowing automobile companies to integrate it into new or existing vehicle development lines without the extra cost of design alterations. This allows many of the global car manufacturers to adopt this AMAT technology easily with minimal effort whether for electric SUVs, delivery vehicles, or future autonomous fleets significantly reducing the barrier to widespread implementation.

For us to determine the future need for this system, we can use predictive analysis which research indicates a strong growth in airless and adaptive tire technologies over the next 5–10 years. This research is provided by the rising demand for low maintenance, more reliable transport and better performance on varied terrain. While its main purpose is intended for terrestrial vehicles, the AMAT also holds a future potential for robotics and space exploration. Initial prototypes with PLA gyroid cores and micro-servo-controlled treads have shown promise, using flexible materials such as TPU and validating them through platforms such as ANSYS. Overall, it presents a scalable and practical solution for today's automotive challenges while enabling future innovation and Custom Tuning.

Introduction

Our Automotive world is evolving at an increasing rate as electric and autonomous vehicles become more practical and sold as a mainstream product. As these become more in use the idea of low maintenance has also become a critical design factor for tires. Traditionally, the pneumatic tires we all know and are used to have been dominating the market since its development; however, these are limited by their inability to adapt to basic surface irregularities or dynamically changes that can happen with weather conditions and so on. This paper introduces the Adaptive Morphing Airless Tire (AMAT), a modern, sensor driven, and servo actuated solution that overcomes these challenges through advanced structural engineering and smart control systems which make both our roads safer and our customization unlimited, whether for basic road journeys or adjusting the grip and corner approaches for racing, these are just a few examples for endless possibilities.

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Gyroid Lattice Core

Structural integrity without air pressure, the AMAT's core uses a gyroid lattice structure which is part of the family of triply periodic minimal surfaces (TPMS). TPMS is well known for the stress dispersion, self-supporting and mechanical efficiency characteristics which make it ideal for 3D printing. When implemented using elastomeric materials such as TPU or carbon-fiber-reinforced nylon, the main gyroid structures offer.

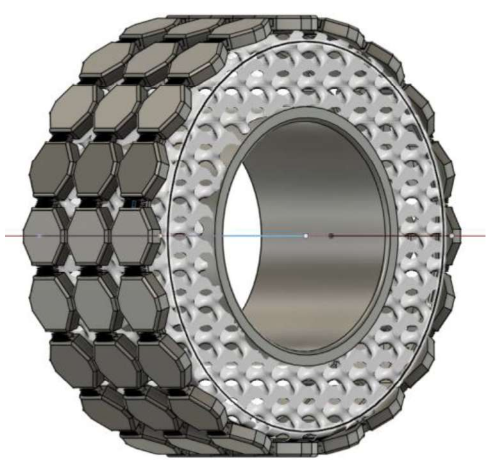

Figure 2 CAD Design with basic TPMS Gyroid Structure

For our main design process, we used TPU (Thermoplastic Polyurethane) 3D Printed Gyroid Structure Which Involves a material Standard TPU (e.g., Shore 95A hardness). The Printing Method uses *Fused Deposition Modeling* (FDM) or Selective Laser Sintering (SLS) which has a relative density of ~30–50% with an approximate Unit Cell Size: 5–10 mm typically. The TPU Compressive Strength Range: from 4–8 MPa according to the infill density and the chosen unit cell size which can vary such as (≥50%) which can reach up to 10 MPa.

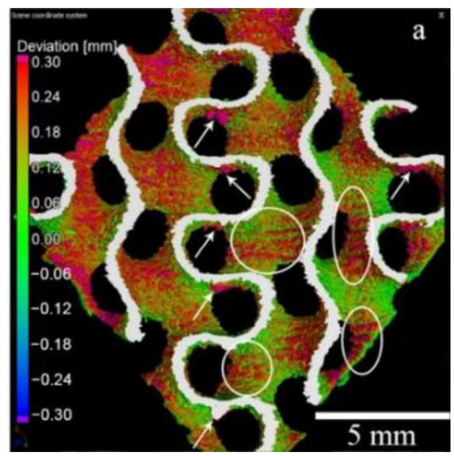

Figure 1 Cross-sectional view of gyroid lattice structure. (Khrapov)

Tire Load Calculations

Let's assume for this calculation a mid-sized electric vehicle that weighs approximately 1.6 tons. The load per tire (for a 4-wheel setup) would be:

$$\frac{1{,}600\ kg}{4} = 400\ kg\ per\ tire \approx 3{,}920\ N$$

So, each tire must handle at least 4,000 N of force while under a steady static compression.

TPU compressive strength = 4–8 MPa and the $Pressure = \frac{Force}{Area}$ → so the area required to safely support 4,000 N:

$$Required\ Area = \frac{Force}{Strength} = \frac{4000N}{4000000\frac{N}{m^2}} = 0.01\ m^2 = 10\ cm^2$$

Meaning our Gyroid lattice structure can safely hold the static vehicle load.

Adaptive Morphing Tread System and Grip Enhancement

The main innovation for the AMAT tire is its outer shell, which consists of independently movable hexagonal modular tread components. These modules are controlled by multiple micro servo motors and can respond to real-time terrain data using input data from LiDAR and visual recognition software optimized to work with any type of modern vehicle.

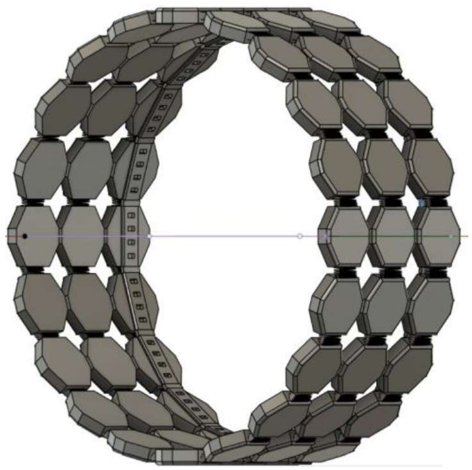

Figure 3 Example concept of morphing tread unit geometry

The main key features include a specific real-time terrain detection with tread module deformation up to ±15 mm Response time < 200 ms. The Grip coefficient with this implementation can increase to 35% in terrains such as (gravel, mud, snow). Including that the attack angle control for improved cornering and slope climbing is a complete game changer.

Sensors send data to the micro controller or ECU to process the data and determine which section should expand or contract with a slight margin of error, which will allow us to adapt the tire's surface to the relevant terrain, increasing safety and reliability preventing unnecessary crashes. More options can also include custom tuning, which allows for optimization according to speed, grip, energy efficiency, or comfort.

Each tread is controlled using a rail connection with all tire threads including a living hinge interconnection, allowing us to push out the threads and contracting them to any given diameter in the range of gyroid elasticity.

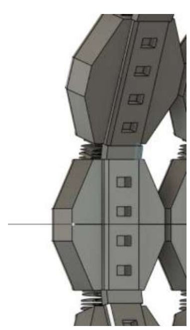

Figure 4 Interlocked Living Joint Treads

To explain how this main innovation works, the adaptation for the tire treads take place through a continuous and nonstop feedback loop between the sensor data input received then provided to the ECU or microcontroller and the motion of the actuators. For example, when the vehicle comes across a certain loose or soft terrain like sand or gravel, the sensors instantly detect that there is a slightly higher vertical movement and different surface depth. The microcontroller this data to receives this data and then can determine that there must be an increased surface area and flexibility for the tire treads to compensate for the geological change. After That it can activate the simple rail systems attached to the servo, expanding the tread modules that are needed and improving the surface contact area with the ground or adjacent terrain. This adjustment will increase the grip and reduce the chance of any slippage, thus for increasing safety. When going back to a smooth asphalt surface, the treads retract which can reduce rolling resistance and can improve energy efficiency for all vehicles in general.

Regarding the behavior of the attack angle for treads in real time, it can be adjusted accordingly. For example, during a sharp turn the lateral sensors can detect a change in the main inertia and body roll, which can trigger selective contraction and expansion of the main treads. This in turn increases the grip on the outer edge of the tire, improving aggressive entering for cornering stability and helps reduce the tire shear forces. And overtime, the system will be able to teach users driving habits and specific routes using machine learning, which can allow it to adjust the tread behavior before the terrain even occurs. This anticipatory control model not only boosts safety but also improves ride quality and prolongs tire lifespan.

Mechanical Validation with ANSYS

Some simulations were performed using ANSYS Workbench to ensure that the AMAT system's structural integrity would work in real-world operating conditions. These simulations were designed to validate the gyroid lattice core's performance under static, cyclic, and thermal stress situations that would be representative of actual driving loads. The models were created with realistic TPU material properties, including elasticity, temperature sensitivity, and fatigue behavior.

Static Stress Testing, under a typical load case which ranges from 500 to 2,000 N per segment, our simulations indicated that the highest von Mises stress values remained below 8 MPa at maximum compression. This is withing the safe operating limits of TPU (compressive strength 4–10 MPa), showing that the gyroid structure can handle high loads without failure and can prove to be reliable. The Stress distribution through the gyroid was mainly uniform across the lattice nodes geometry of the TPMS structure, which reduces the localized failure points.

Fatigue Testing, Cycle simulations with over 50,000 operational cycles. The gyroid structures exhibited a valid structure to us, with stiffness of 10%. The AMAT structure did not exhibit deformation, or any plastic deformation were observed within the loading range. The AMAT's core can withstand long use without a decline in performance, even under severe or harsh conditions.

Thermal Stability, the TPU material simulations within the ANSYS program considered the surface temperature changes, ranging from -30°C to 120°C. Even at very severe temperatures, the gyroid lattice maintained its elastic response. This makes AMAT a good solution for a wide spectrum of climates from cold environments to hot desert terrains.

Overall, the computer aided ANSYS simulations analysis proves that AMAT's gyroid core meets the required mechanical safety standards that we need. These results provide a strong base to start prototyping and transitioning the design into practical manufacturing workflows.

AI and Sensor-Based Terrain Classification

AMAT adaptiveness depends on the system and network of sensors and machine learning algorithms. The terrain feedback information can be determined by using:

<u>LiDAR:</u> Scans for surface irregularities and terrain scanning determining how far the determined terrain is and how much it must compensate for.

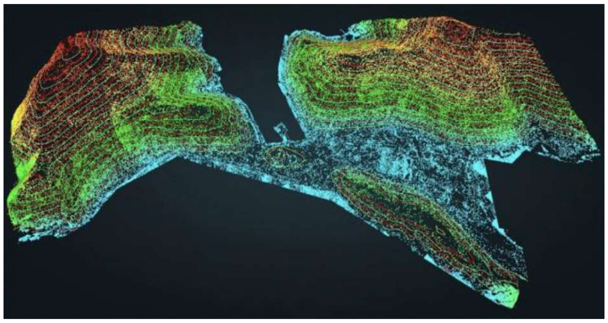

Figure 5 LiDAR Scanning Terrain EX. (Segarra, June 6, 2023)

<u>Cameras</u>: Helps the machine learning system visual and determine what environment it is dealing with (rainy, snowy, how, icy and so on). Combining the LiDAR data as well to analyze accurately how far and how much correction should be made.

<u>IMUs</u>: Monitors the automobiles' motion and detect if there is any slip or instability in the vehicle.

All the data gets put into a terrain classification model that has been trained in a way that uses supervised learning techniques. Then afterwards the AI can decide which terrain type we are faced with (mud, gravel, sand, asphalt) and then send instructions to the treads to readjust according to the data received. This allows us to do real-time, localized optimization of grip and comfort.

Vehicle Integration and Customization Option

The AMAT tire was designed for the intention of seamless entering and being implemented into the current automotive production lines. The main features that will be included are *Hub Compatibility,* which will Fit all standard 5-lug and 6-lug wheels, *Low Power Draw*, which will draw a minimum of <12W per tire under full load, not to mention also the scalability, which is customizable for different wheel sizes (14" to 22"), tread optimization which can be tuned using the vehicle software which can prioritize different modes such as off-road, sport, snow, or economy.

Conclusion

The AMAT system is a major advancement in tire technology by using intelligent control systems with adaptive structural materials. Using heavily researched topics that include gyroid lattice cores and new innovations such as the servo-actuated, terrain responsive treads, AMAT increase safety while delivering real-time modification to changing surfaces and terrains. This significantly improves the vehicle performance, safety, and reliability in many conditions it gets exposed to. All supported constant simulation data and engineered for scalability, AMAT is considered as both a practical and forward-thinking solution for modern mobility.

Its modular design allows for smooth integration with existing vehicle platforms without requiring massive or major modifications, making it ideal for many mainstream and commercial electric vehicles, autonomous systems, off-road transport, and in the future space exploration. AMAT's AI terrain scan, combined with real-time adjustment, allows for optimization of grip, energy usage, and stability, for both urban roads and rugged environments.

As material and sensor technologies evolve, AMAT stands not only as a research success for the future but as a innovation with the potential to become a future industry standard which will reshape how vehicles interact with the terrain beneath them.

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Author's Contributions

All research development, testing and production were designed by Waseem Imad Fanous.

Ethics

The product follows all the ethics and standards provided by the BOSH organization.

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