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LOCOMOTION UNITS AND METHODS OF ACHIEVING LOCOMOTION IN TETRAHEDRAL-STRUCTURE ROBOTS

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Abstract: *The paper presents a comparative evaluation of various locomotion units, ranging from standard wheels to complex omnidirectional designs, using criteria such as energy efficiency, cost, vibration levels, structural complexity, and compatibility with the overall structure. The results indicate that the spherical Omni-Ball locomotion unit represents the optimal solution, providing an ideal balance across all analyzed criteria. Additionally, different locomotion methods are explored, including rolling with or without impact, crawling, and resonance-based motion, highlighting the advantages and limitations of each. The article also proposes innovative solutions, including hybrid systems and a novel configuration in which locomotion units are mounted on the faces of the tetrahedron to enhance stability. Finally, future research directions are discussed, focusing on the optimization of intelligent control and the development of structures capable of efficiently transitioning between different modes of movement.*

Key words: *mobile robotics, tetrahedral structure, omnidirectional locomotion, rolling, crawling*

1. INTRODUCTION

Locomotion constitutes a fundamental requirement for any mobile robot, representing the essential capability that enables it to move within its operational environment to perform a wide range of tasks, from surveillance and inspection to transport [1].

The selection of the locomotion system is a critical aspect of the design phase, as it directly determines the robot’s mobility, maneuverability, and energy efficiency, factors that are strongly influenced by the specific environment in which it is intended to operate [1] – [3].

The importance of locomotion systems in modern mobile robotics is highlighted by the need for environmental adaptability and maneuverability in confined spaces, where omnidirectional locomotion becomes essential for navigating narrow corridors and avoiding obstacles without complex maneuvers [4] – [6].

Specialized locomotion systems enable access to hazardous or otherwise inaccessible areas for human workers and directly influence system autonomy through the optimization of energy consumption [3], [7]–[10].

In this context, robots with a tetrahedral geometry present a series of unique technical challenges, arising from their symmetric structure and motion systems based on deformation or tipping.

Among the major identified difficulties are the precise management of the center of mass [12] – [14], the control of over constrained structures [15] – [18], which require rigorous synchronization, and the need to find a balance between structural rigidity and the deformability required for locomotion [19].

The aim of this article is to analyze locomotion units from the specialized literature, to select the most suitable solutions for tetrahedral-structured robots, to conduct an in-depth study of their locomotion mechanisms, as well as to propose new locomotion modalities.

The structure of the paper includes an introduction to the context of tetrahedral robots, a description and comparative analysis of locomotion units, an exploration of motion implementation methods, the proposal of new hybrid configurations, and a final section dedicated to conclusions and future research directions.

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2. LOCOMOTION UNITS

Locomotion units represent the fundamental systems that enable mobile robots to perceive, make decisions, and execute movements to achieve autonomy in various environments, directly determining the system's maneuverability and stability [20].

These are primarily classified into standard wheels and omnidirectional wheels, each category featuring specific structural characteristics that influence the robot's performance.

2.1. Standard wheels

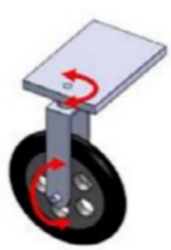
These units are defined by nonholonomic constraints, having the ability to move exclusively in a direction perpendicular to their central axis [20].

This category includes standard wheels, presented in Figure 1a [21], valued for their simple design and versatility, as well as simple swivel wheels, shown in Figure 1b [20], which allow rotation in two directions in an almost simultaneous manner, and spherical-geometry swivel wheels (Figure 1c) [20], which are considered more reliable due to their larger contact surface with the ground.

The differential-driven swivel wheel design (Figure 1d) [22] uses a complex system of cylindrical gears to optimize motor performance and reduce the overall size of the robot.

Although these wheels are used in multiple fields due to their advantages, the literature highlights that standard wheels do not represent an optimal solution for tetrahedral robots, since these systems have a limited number of contact points with the ground, which complicates directional control and may increase energy consumption.

a)



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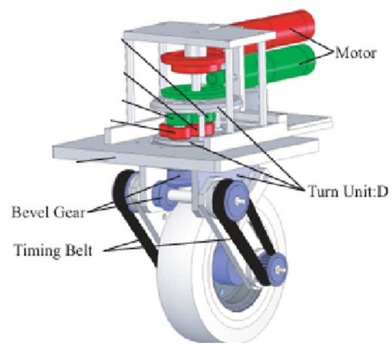


d)

Figure 1. Standard wheels; a) classic wheel [21], b) simple swivel wheel [20], c) spherical swivel wheel [20], d) differential-driven swivel wheel [22].

2.2. Omnidirectional locomotion units

Omnidirectional wheels, essential for holonomic mobile robots, enable movement in any direction on a flat surface without changing the orientation of the chassis [6].

Universal wheels (Figure 2) represent an important subcategory, being composed of passive rollers mounted at 90 degrees relative to the main axis [20]. These include active variants (Figure 2a), where the peripheral rollers are directly driven through helical gear mechanisms [23], simple variants (Figure 2b) with passive actuation [24], and double variants (Figure 2c), which use staggered rows of rollers to ensure continuous ground contact and reduce vibrations [24].

Advanced models such as the Continuous Alternating Wheel (CAW), shown in Figure 2d, minimize vibrations through the partial overlap of large and small rollers [25], [26], while the "Laquos" design (Figure 2e) uses flexible tubes to adapt to ground irregularities [27], and the "WESN" model (Figure 2f) employs conical rollers that are activated only during transverse motion [28].

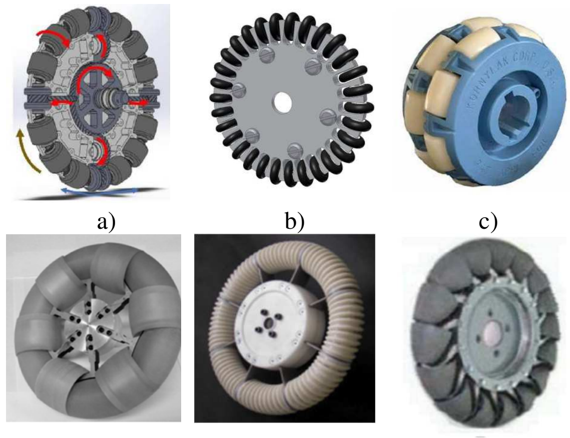


Figure 2. Universal omnidirectional locomotion units; a) active [23], b) simple [24], c) double [24], d) continuous alternating [25], e) Laquos [27], f) WESN [28].

Another omnidirectional locomotion solution is represented by Mecanum wheels (Figure 3a), which feature barrel-shaped rollers oriented at a 45-degree angle, being capable of supporting heavy loads and providing superior maneuverability in confined spaces [5], [20].

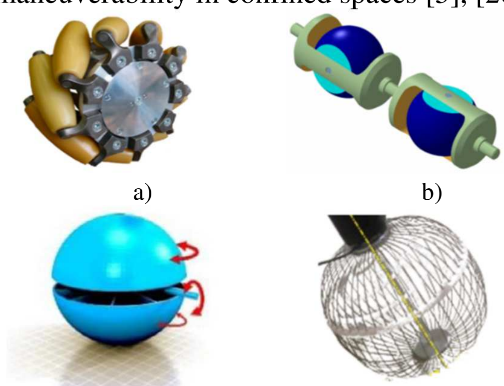


Figure 3. Various omnidirectional locomotion units; a) Mecanum [20], b) orthogonal [6], c) spherical [29], d) globular [30].

Orthogonal locomotion units (Figure 3b) typically use two truncated spheres or discs offset at 90 degrees to ensure smooth rolling, their evolution being marked by the MY series, which culminates in designs forming a complete sphere composed of multiple rotating rings [6].

The spherical omnidirectional locomotion unit (Figure 3c), known as the Omni-Ball, consists of an active shaft and two passive hemispheres.

This unit is considered highly suitable for tetrahedral robots because it provides smooth motion and maintains constant contact with the ground even when the shaft is tilted, overcoming the limitations of other omnidirectional systems that may become unstable in such configurations [29]. Another locomotion unit found in the specialized literature is the globular locomotion unit (Figure 3d) with metal spikes, designed to provide mobile robots with omnidirectional mobility on rough terrain [30].

3. ANALYSIS OF LOCOMOTION UNITS COMPATIBLE WITH TETRAHEDRAL ROBOTS

The selection of a propulsion system for tetrahedral-structured robots represents a challenge, driven by their specific geometry, which requires efficient operation regardless of the robot's orientation on the rolling surface.

A comparative analysis of existing solutions was carried out based on five key criteria: cost, energy efficiency, vibration level, structural compatibility, and design complexity. The evaluation was conducted under the scenario in which the locomotion units are arranged as shown in Figure 4, namely at each vertex of the tetrahedron.

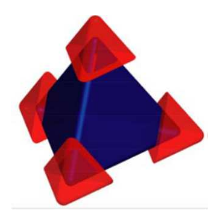


Figure 4. Arrangement area of the locomotion units [29]

In this context, two tables were developed: Table 1 presents the analysis in terms of cost, energy efficiency, and vibration level, while Table 2 highlights the evaluation of the same locomotion units according to structural compatibility and design complexity.

Table 1

Analysis of locomotion units from the perspective of cost, energy efficiency, and vibration level

Locomotion unit	Costs	Energy efficiency	Vibration level
Classical	Low	High	Low
Active	High	Low	High
Simple	Low	Medium	High
Double	Medium	Medium	Medium
Continuous alternative	Medium	High	Low

Laquos	High	Medie	Low - Medium
WESN	High	Medium	Low
Mecanum	High	Low	High
Orthogonal	High	Low	Medium
Spherical	Low	High	Low
Globular	Low	Low	High

Table 2

Analysis of locomotion units from the perspective of structural compatibility and design complexity

Locomotion unit	Structural compatibility	Constructive complexity
Classical	No	Simple
Active	Yes	Complex
Simple	Yes	Simple
Double	Partial	Medium
Continuous alternative	Yes	Medium
Laquos	Yes	Complex
WESN	Yes	Complex
Mecanum	No	Complex
Orthogonal	No	Complex
Spherical	Yes	Simple
Globular	Yes	Simple

The technical analysis of the main solutions highlights the following conclusions:

The most suitable solution is represented by the spherical locomotion unit (Omni-Ball). According to the performed analysis, it is the only solution that meets all optimal criteria: it has a relatively simple construction, high energy efficiency, full compatibility with the tetrahedral structure, low vibration levels, and low associated costs.

Within the universal locomotion unit category, the CAW (Continuous Alternating Wheel), Laquos, and WESN models stand out as the most high-performing solutions. Among them, the CAW unit is particularly notable for significantly reducing vibrations and for its superior ability to overcome obstacles, due to its interleaved roller-based design.

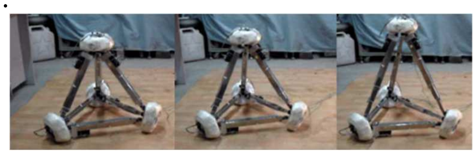
In contrast, conventional wheels, as well as Mecanum and orthogonal systems, are considered unsuitable for the tetrahedral structure when locomotion units are mounted according to Figure 4. Conventional wheels provide limited ground contact and are prone to slipping during directional changes [29], while Mecanum or orthogonal systems are heavy and difficult to control within a tetrahedral configuration [20].

4. METHODS OF ACHIEVING LOCOMOTION IN TETRAHEDRAL ROBOTS

Among the main locomotion methods are rolling locomotion, with or without impact, crawling (achieved by the successive modification of support points), and motion based on exploiting the resonance phenomenon.

Impact-based rolling locomotion involves tipping the robot over an edge by shifting the center of gravity outside the support base [14].

The process consists of three stages: the deformation phase (extension of the arms) (Figure 5a), the falling phase (tipping under the action of gravity) (Figure 5b), and the recovery phase (returning to the initial shape) (Figure 5c) [13].



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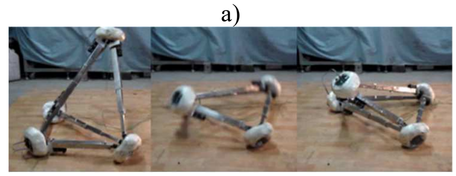

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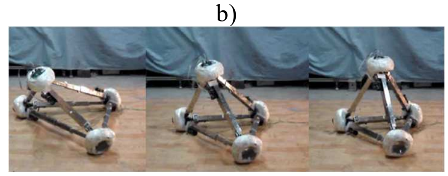


c)

Figure 5. Stages of impact-based rolling [13]; a) deformation phase, b) falling phase, c) recovery phase.

Although it is a highly energy-efficient method (with savings of over 60% compared to crawling), repeated impact generates vibrations and mechanical wear [14].

Locomoția prin rostogolire fără impact este o strategie avansată care elimină șocurile mecanice prin menținerea unui control continuu [31]. The robot deforms its structure so that a new face contacts the ground before the previous base is lifted, ensuring a smooth transition. This method significantly reduces positioning errors and protects sensitive payloads, but it requires a high degree of arm deformability [11], [31].

Non-impact rolling also occurs in three stages: the robot deforms its structure to bring a new face into contact with the ground before the current face is lifted, making the new support area coplanar with the previous one (Stage 1 – Figure 6a); the center of mass is then deliberately shifted from the old support area to the new one while both remain in contact with the ground (Stage 2 – Figure 6b); once the center of mass is secured within the new support region, the previous contact points are lifted and the robot returns to its initial shape (Stage 3 – Figure 6c).

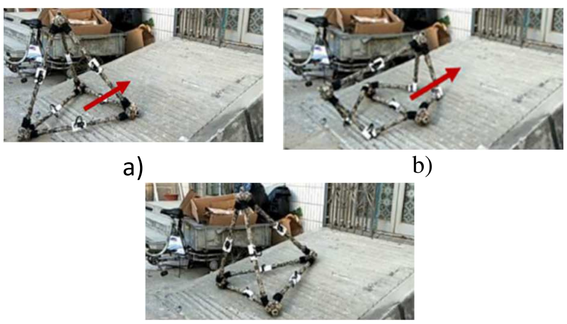


Figure 6. Stages of non-impact rolling [11]; a) stage 1, b) stage 2, c) stage 3.

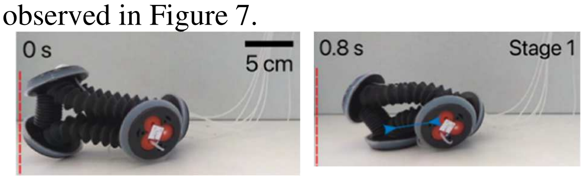
In simulation experiments, non-impact rolling demonstrated a reduction in the positioning error rate (the transverse error decreased from 6.61% to 3.74%, and the longitudinal error from 8.29% to 2.94% compared to impact-based rolling) [11].

Eliminating impact prevents energy losses and protects the robot against structural damage, making it an ideal method for transporting sensitive payloads [11].

Crawling locomotion, inspired by animal biomechanics, provides higher stability compared to rolling and enables navigation through very narrow spaces [19].

Although it enables precise approach to the target, crawling is considered the slowest and most energy-inefficient method due to the constant friction between the limbs and the ground [14].

The crawling locomotion process can be observed in Figure 7.



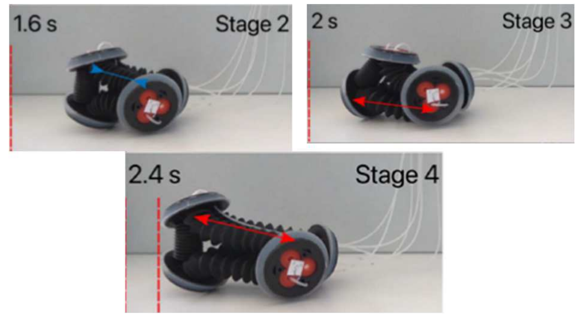


Figure 7. Tetrahedral robot locomotion through crawling [19]

Resonance-based locomotion, exemplified by the Tetrabot project, uses oscillations of a central mass suspended by springs to generate motion [32].By exciting its natural vibration modes, the robot can perform hopping or sliding motions [32]. Resonance-based robot locomotion is shown in Figure 8, where the robot moves on a flat surface for 20 seconds. The authors report that the maximum speed of the robot reaches 2.3 m/min [32].

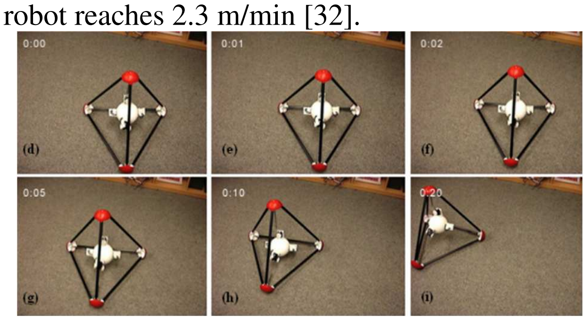


Figure 8. Resonance-based robot locomotion [32]

A major advantage is that the entire mechanism can be fully enclosed within a casing, protecting it from harsh environments (dust, mud, etc.) [32].

5. PROPOSAL OF NEW TETRAHEDRAL ROBOT DESIGNS

The new research directions focus on the development of hybrid locomotion units capable of combining the advantages of omnidirectional systems with the internal locomotion mechanisms specific to tetrahedral robots. At the same time, alternative configurations are being explored in which the locomotion units are mounted on the faces of the tetrahedron, instead of being positioned at the vertices, as is predominantly encountered in the specialized literature.

Figure 9 illustrates a schematic variant of a hybrid locomotion robot proposed by the authors, which is particularly advantageous for movement on flat surfaces, where the omnidirectional units ensure higher speed and superior stability. In contrast, in challenging situations such as overcoming obstacles or climbing steps, adaptation through structural deformation allows the robot to avoid getting stuck and to maintain its mobility.

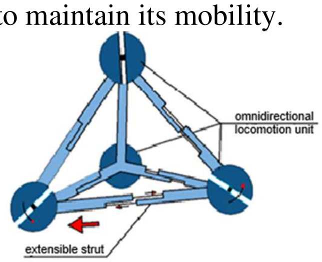


Figure 9. Proposal of a new hybrid locomotion solution for the tetrahedral robot.

In Figure 10, the authors present a schematic of a new configuration for the arrangement of locomotion units in a tetrahedral structure. In this configuration, the units are mounted on the faces of the tetrahedron, which enables more stable movement and extended compatibility with various types of omnidirectional units.

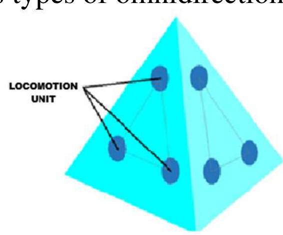
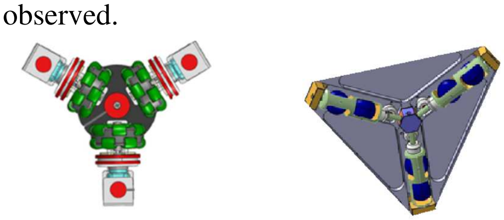


Figure 10. Proposal of a new solution for the arrangement of locomotion units.

Examples of implementation of this configuration are illustrated in Figure 11a, where a possible arrangement of dual universal locomotion units on each face of the robot is presented, and in Figure 11b, where a variant arrangement of orthogonal locomotion units can be observed.



a) b)

Figure 11. Examples of the arrangement of locomotion units on the faces of the tetrahedron [2]; a) double universal omnidirectional units, b) orthogonal omnidirectional units [33]

6. CONCLUSIONS AND RESEARCH DIRECTIONS

Locomotion represents the fundamental ability of a robot to navigate and perform tasks in various operational environments.

The paper highlights the complexity of the design of these systems and the importance of choosing an optimal solution to ensure the balance between mobility, stability and energy efficiency.

The mobile robot with a tetrahedral structure relies on a harmonious integration between a versatile locomotion unit and a control algorithm capable of managing structural deformations.

Future research directions aim at the development of hybrid locomotion units capable of combining the advantages of omnidirectional wheels with the specific movement systems of tetrahedral robots. Optimizing the balance between rigidity and deformability, especially in the case of robots that move through the extension–contraction of their edges. The development of intelligent control systems capable of switching between different locomotion modes depending on environmental requirements.

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Unități de locomoție și modalități de realizare a locomoției roboților cu structură tetraedrică

Rezumat: Lucrarea evaluează comparativ diverse unități de locomoție, de la roți standard la modele omnidirecționale complexe, folosind criterii precum eficiența energetică, costurile, nivelul de vibrații, complexitatea constructiva și compatibilitatea structurală. Rezultatele indică faptul că unitatea sferică de tip Omni-Ball reprezintă soluția optimă, oferind un echilibru ideal între toate criteriile analizate. De asemenea, sunt explorate modalități de locomoție precum rostogolirea cu sau fără impact, târârea și deplasarea bazată pe principiul rezonanței, subliniind avantajele și limitările fiecăreia. Articolul propune soluții inovatoare, inclusiv sisteme hibride și o nouă configurație cu unități de locomoție dispuse pe fețele tetraedrului pentru o stabilitate sporită. În final, sunt discutate direcțiile viitoare de cercetare care vizează optimizarea controlului inteligent și dezvoltarea unor structuri care să alterneze eficient între diferite moduri de deplasare.

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