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Assembly and implementation of modular quadrupedal architecture

Ensamblaje e implementación de arquitectura cuadrúpeda modular

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ABSTRACT

This paper describes a quadrupedal architecture assembly process using the modular robotic system Mecabot. Several possible topologies are considered, justifying the final design that allows using an active column. Based on this, a mathematical model of control is proposed to perform movements of displacement, open turn and rotation. The locomotion profiles for the first two movement modalities are bioinspired. For the rotation modality, a characteristic quadrupedal robot transition is used to allow the correct rotation without using a large number of degrees of freedom. The proposed control model was deployed in a robot tested on structured and unstructured terrains by measuring its speed as a function of the movement frequency variation. For the open turn modality, the turn radius was measured as a function of the offset variation. Based on the test results, the second Mecabot configuration with legs was finally obtained, complementing our research work on apodal (snake, wheel caterpillar) and hexapod configurations.

RESUMEN

En este documento se describe el proceso de ensamblaje de una arquitectura cuadrúpeda utilizando el sistema robótico modular Mecabot. Varias posibles topologías son abordadas para finalmente optar por un diseño que permita emplear una columna activa. En base a ello es planteado el modelo matemático del control para realizar los movimientos de desplazamiento, giro abierto y giro cerrado. Los perfiles de locomoción que debe ejecutar el robot para estas dos primeras modalidades de movimiento son bioinspirados. Para la modalidad de giro cerrado se emplea una transición característica de los robots cuadrúpedos con el fin de poder seguir ejecutando correctamente la rotación sin necesidad de emplear un número mayor de grados de libertad. El robot es probado en terrenos estructurados y no estructurados midiendo su velocidad en función de la variación de la frecuencia de movimiento, para la modalidad de giro abierto se mide el radio de la circunferencia descrito en función de la variación del offset. Con las pruebas realizadas finalmente se obtiene la segunda configuración con patas implementada en el Mecabot, complementando así los trabajos de investigación previamente realizados para la configuración hexápoda y configuraciones ápodas (serpiente, oruga rueda).

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1. Introduction

Robots are typically designed to support human activities, perform tasks beyond human physical capabilities, and reach difficult-to-access places. Robots can be divided into countless categories, depending on their applications. Mobile robots break the anchoring scheme that is evident in industrial robotics and allow service-oriented applications [1].

Among the many research directions in robotics, the most prominent are bioinspired designs and modular units. The bioinspired approach applies the fundamental principles of living beings to the robotic field, while modular units are less expensive and simpler structures with greater adaptability [2–4].

This paper proposes a mobile robot architecture based on bioinspired mechanisms of quadrupedal and tetrapodal animals. To implement the architecture, the fifth version of modular robots created by the Davinci research group (Military University Nueva Granada) were used.

Module robots were first developed 39 years ago. They can perform an unlimited number of operations depending on their morphology, which can be divided into one-dimensional (1D) lattice, three-dimensional (3D) chain, and hybrid (1D+3D). Furthermore, there are two types of robot configurations, namely, mobile and full-body. The mobile configuration includes independent modules that can interact with the environment. On the other hand, the full-body configuration requires other modules to enable robot mobility and interaction with the environment [5, 6].

Many types of modular, quadrupedal robots have been developed. Popular robot morphologies include the spider and lizard configurations, used in the *Polybot* robot, the mammal-based configuration, used in the CKBot, the swerve drive (wheel-legs) configuration, used in the *SMORE-EP* and the centaur configuration, used in the Walbot [3], [7–11].

Among modular quadrupedal robots, hybrid robots with capabilities not limited to terrestrial locomotion are getting a lot of attention. The salamander family has been considered for many designs because it can perform water/land/climb transitions. Examples of salamander-based robots include the Amphibot (modular), Pleurobot (non-modular), Chigon (non-modular), bioinspired salamander (modular) robots, AMOS WD02 (non-modular), StickyBot (non-modular) and robots based on the Chinese dragon, Pleurodeles walt, crytobranchidae and gecko [12–16].

The existing approaches to designing salamander-based robots vary in their levels of fidelity, which determine the similarity between the robot and the animal. A higher fidelity implies more degrees of freedom (DOFs) and more complex controllers. For example, the Pleurobot simplifies many column DOFs; however, it has four DOFs per leg and 11 DOFs in the column, including a tail with a fin and a sophisticated scapula design. On the other hand, the AMOS WD02 has only two DOFs per leg and one DOF in the column. Typically, a robot's architecture depends on its mechanical design and investigation purpose. Modular robots are limited by module couplings [15], [17].

The rest of this paper includes the following sections: investigation project, architectural approach methodology, displacement approach methodology, implementation and results and conclusions.

2. Investigation project

The Mecabot robot is a project developed by the Military University Nueva Granada (Bogotá - Colombia) since 2013. The Mecabot modular unit consists of two sub-modules, each made up of a body and a pivot.

Four different types of couplings can be realised using these sub-modules; three of them allow linear union (face-face, pivot-pivot, face-pivot) and one allows perpendicular union (two lateral faces by pivot connection or face connection).

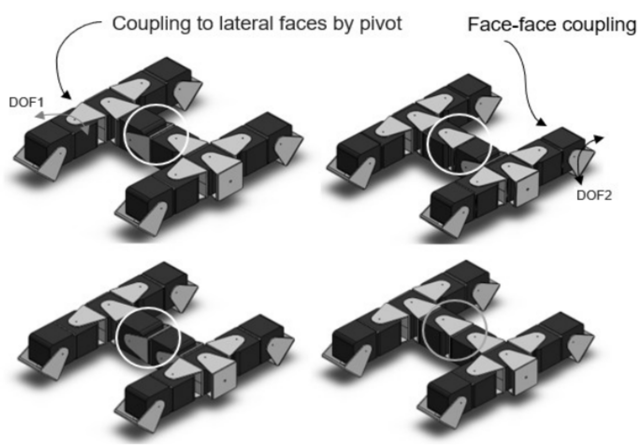
The Mecabot is designed to perform exploration, search and rescue. To expand the robot's adaptability capacity, different architectural assemblies have been studied (snake, caterpillar, wheel and hexapod). The robot's hexapod configuration has already been tested on unstructured terrain and other topologies, while the quadruped and biped configurations (i.e. with legs) are currently under investigation [18–20]. This paper reports on the results of comprehensive simulations and mathematical analyses.

3. Methodology for the architecture approach

In general, a quadrupedal robot has three different limb arrangements: perpendicular to the advance direction (frontal), parallel to the advance direction (sagittal) and radial to the robot's body (circular). Among these arrangements, the frontal provides the most stable base (a characteristic of reptiles). In contrast, the sagittal arrangement requires the greatest stability control (a characteristic of mammals). At the same time, the sagittal arrangement allows high speeds on flat terrains since its energy consumption is low [21]. To enable a good performance on difficult surfaces, the frontal arrangement was chosen for the Mecabot, while the energy consumption was reduced by employing only two DOFs per leg.

The frontal quadrupedal topology was developed based on the four couplings types that the Mecabot can adopt. To allow its legs to reach the highest possible degree of openness, a coupling to lateral faces by pivot connection was used (Figure 1). Its spine length was built in order to enabled movements in the range of $\pm\pi/2$ $\pi/2$ in each extremity. Each leg is composed by two modules and its spine has same number of modules too. In this order of ideas, when the leg reaches its maximum position, the leg's extreme will match with spine middle point.

Figure 1: Possible configurations in the central semi-modules of the column used in the Mecabot. Top: Inverted pivot-face retaining the second semi-module (left) and first semi- module (right). Bottom: Connection to the inverted scapula (left) and without inverting (right).



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The second DOF of the legs can be assembled using a face-pivot coupling or a face-face coupling. With the face-pivot coupling, the robot would reach a height of 17.4 mm above the ground; with the face-face coupling, it would be 36.4 mm. To ensure a sufficient height of the Mecabot and facilitate its manoeuvrability on unstructured terrain, the face-face coupling was chosen (Figure 1).

For the two modules in the spine, the pivot-pivot connection was avoided due to its structural weakness. Furthermore, using the face-face coupling would implicitly involve pivot-pivot connection. Hence, the face-pivot coupling was chosen.

There are four possible architectures when employing the face-pivot coupling, as shown in Figure 1. Among the four architectures, the topology using non-inverted couplings would allow using an active column, the movement of which would provide the step length. Under these conditions, neither the legs nor the spine would have to adopt angles close to the motor mechanical limits, and they would not be forced at high speeds. Hence, the topology with non-inverted couplings was finally chosen for the spine.

4. Methodology for the displacement approach

The so-called standard gait provides quadrupedal robots with the best static stability. It is the only one that is evidenced in nature and used by some animals in their slow movements [22]. The robot's movement, using the active column, can be implemented based on the numerous locomotion studies on salamanders. Salamanders use a lateral sequence, which corresponds to the standard gait with a high support factor. In this lateral sequence, the following column- leg coordination aspects must be guaranteed [23, 24]:

- The column must reach the maximum contraction after the hindlimb's transition phase ends.
- The beginning of the forelimb's transition phase must coincide with the maximum retraction of the diagonally opposite hindlimb.
- The lifting (i.e. the transition phase) is carried out only in protraction.
- Protraction is faster than retraction.

These points must be fulfilled to ensure the robot's stability during the step sequence. When the animal flexes the spine, the centre of gravity moves from one side to another, and therefore, the transition and support phases of the legs must be coupled to this change. However, these requirements result in complex locomotion profiles.

In this study, we designed the movement profiles between the legs and the spine based on direct observations of salamander movements. For this purpose, the complementary material published by the researchers from the École polytechnique fédérale de Lausanne (*Movie S5 Tracking for Pleurodeles waltlii in* *cineradiographic recordings*) were used. This video was taken using innovative X-ray techniques to analyse the salamanders' bony movement [17].

From a 15 s video, a 5 s fragment corresponding to the movement cycle was taken. Since the Mecabot was designed to have only two DOFs, the salamander legs were analysed only in the *Top View* of the video. There are four points of interest in the tracking video; only one of these was chosen for each leg, and the angles adopted in these points were extracted over time. The Mecabot's control mechanism was programmed based on the extracted profiles.

4.1. *Simple displacement control mechanism*

There is a variety of different strategies for modular robot control. Among these strategies, the Central Pattern Generators (CPGs) allow executing complicated movements with few control parameters and lack of feedback. Moreover, the CPGs provide a smoother, more harmonious response than traditional methods. However, they involve a high computational cost, while their directly bioinspired mechanisms tend to be redundant [18, 25, 26].

The sinusoidal generators are simplified versions of the CPGs, and have been used in the snake and caterpillar Mecabot configurations, providing good results. In particular, the sinusoidal generators involve fewer calculations while keeping the benefits of the CPGs. The adopted form of the sinusoidal generators for the column control can be expressed as [13, 27]

$$\theta_i = -\left(A_i * \sin\left(\pi * F * t * bias_i\right) + offsett_i\right) \tag{1}$$

While the legs movement profile is more elaborate than the column profile, the adopted controller also allows some variation in frequency, bias and amplitude. In particular, the sum of the sine interpolations of the data extracted for the video was used to create the *composite sinusoidal generator*, as follows:

$$\theta_i = E1 + E2 + E3 + E4 \tag{2}$$

$$E1 = A_i * \sin(\pi * F * t + bias_i)$$

$$E2 = \frac{A_i}{2} * \sin(2\pi * F * t + 2bias_i)$$

$$E3 = \frac{A_i}{3} * \sin(3\pi * F * t + 3bias_i)$$

$$E4 = \frac{A_i}{8} * \sin(4\pi * F * t + 4bias_i)$$

4.2. *Control mechanism for performing open and closed turns*

The simplest method for performing an open turn is to vary the offset in the column sinusoidal generators [13, 23, 24]. When the *offset* is non-zero, the robot follows a circular path, in the left or right direction, depending on this variable sign. During the turn, the times taken by the centre of gravity on both sides in relation to middle (head-tail) axis of the transverse (horizontal) plane are no longer equal. In other words, the time of the leg transition phase should vary, depending on this time difference; otherwise, the robot would lose its stability.

The transition phase time for the legs located on the rotation side should be increased, while that for the legs on the opposite side should be decreased. To achieve this, the ascending slope (protraction) of the sinusoidal generators should be allowed to increase or decrease. Based on the analysis of the proposed interpolation presented in formulae (2), this flexibility can be ensured by varying the number of En terms. For the open turn, the following two types of *composite sinusoidal generators* are proposed:

$$\theta_i = E1 + E2 + E3 \tag{3}$$

$$E1 = A_i * \sin(\pi * F * t + bias_i)$$

$$E2 = \frac{A_i}{2} * \sin(2\pi * F * t + 2bias_i)$$

$$E3 = \frac{A_i}{3} * \sin(3\pi * F * t + 3bias_i)$$

$$\theta_i = E1 + E2 + E3 + E4 + E5 \tag{4}$$

$$E1 = A_i * \sin(\pi * F * t + bias_i)$$

$$E2 = \frac{A_i}{2} * \sin(2\pi * F * t + 2bias_i)$$

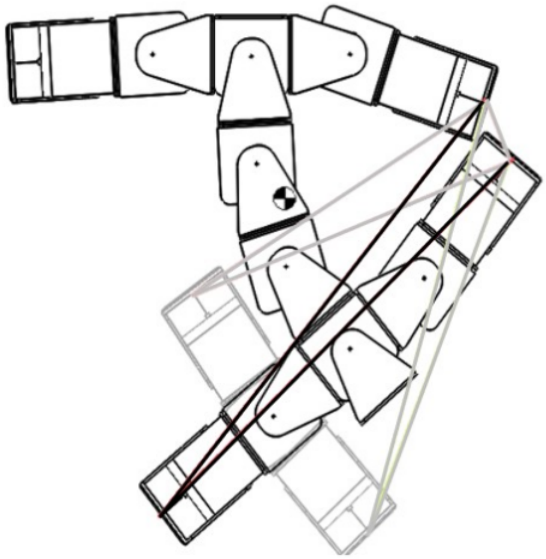
$$E3 = \frac{A_i}{3} * \sin(3\pi * F * t + 3bias_i)$$

$$E4 = \frac{A_i}{4{,}05} * \sin(4\pi * F * t + 4bias_i)$$

$$E5 = \frac{A_i}{16} * \sin(5\pi * F * t + 5bias_i)$$

The increased number of En terms in (4) provokes an increase in the slope and decrease in the time of the legs' lifting phase. The decreased number of En terms in (4) has the opposite effect. Depending on the offset sign, the change of En terms is performed for the corresponding pairs of legs.

Figure 2: Mechanical limitations of the Mecabot: a hypothetical rotation using the active column. Leg 2 is in the air, while the support polygons (represented in black and grey) never reach the centre of gravity.



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To perform the closed turn or rotation, the robot should adopt a higher offset, while its legs, located on the rotation side, would have to remain completely static at a defined maximum opening. Under these hypothetical conditions, the robot is completely unstable; the stability polygon generated by the extremities on the opposite rotation side would not cover the centre of gravity (Figure 2).

Amphibians compensate for this phenomenon by flexing their legs below the abdomen. An additional DOF would be required to replicate this movement in robots, which would increase their weight, energy consumption and programming complexity.

To perform a rotation without losing balance and increasing the cost, the robot's spine should remain motionless during rotation. It is possible to adopt another sequence, namely, progressive transition, which includes the body movement phase or the two-to-two transition. The two-to-two transition is faster than the progressive sequence, and it requires fewer DOFs. To implement this transition, two sinusoidal generators are created as

$$\theta_i = A_i * \sin(\pi * F * t + bias_i) \tag{5}$$

$$bias = \begin{cases} 0, & i = 1,3 \\ -\pi, & i = 2,4 \end{cases}$$

5. Implementation and results

The control algorithms' coordination and correct performance were tested in the Webots simulation environment. The physical modules were then programmed using a decentralised control.

5.1. Results of simple straight displacement

In a simple displacement, six sinusoidal generators were used (four composite generators in the legs and three simple generators in the column). The frequency in all of them was varied, and the linear velocity was measured as a function of this control parameter change. Some tests were performed in three structured areas by varying the level of firmness (using foam as a flat soft surface) and friction (using a sandpaper as a flat rough surface). Further tests were carried out on three unstructured terrains: pavement, rocky and grass; pavement was the least irregular terrain (Figure 3).

From the tests, it was evident that the increased frequency of the six generators resulted in the robot's increased linear speed. The maximum speed was 0.25 m/s. As the difficulty and irregularity of the terrain increased, the speed decreased. On the grass, the robot reached 19.74 % of the Lab Floor maximum speed.

5.2. Results of open turn

In an open turn, six sinusoidal generators were used (four composite generators with variation in the protraction time), the offset of the three generators of the column was varied, and the turn radius was measured as a function of this control parameter change. The tests were performed on one structured terrain and two unstructured terrains (pavement and rocky). From the tests, it was evident that the increased offset resulted decreased the turn radius (Figure 4).

With an offset higher than $\pm\pi/18$, conditions close to instability were present, similar to when the robot performed a rotation with an active column. For this reason, the minimum reached turning radius was 0.4225 m. The radius was generally big since the terrain's irregularity and the surface's ups and downs made the robot divert from its path. The minimum reached turning radius was 0.58 m on the pavement and 0.765 m on the rocky terrain.

Figure 3: Relation between Linear Velocity and Frequency

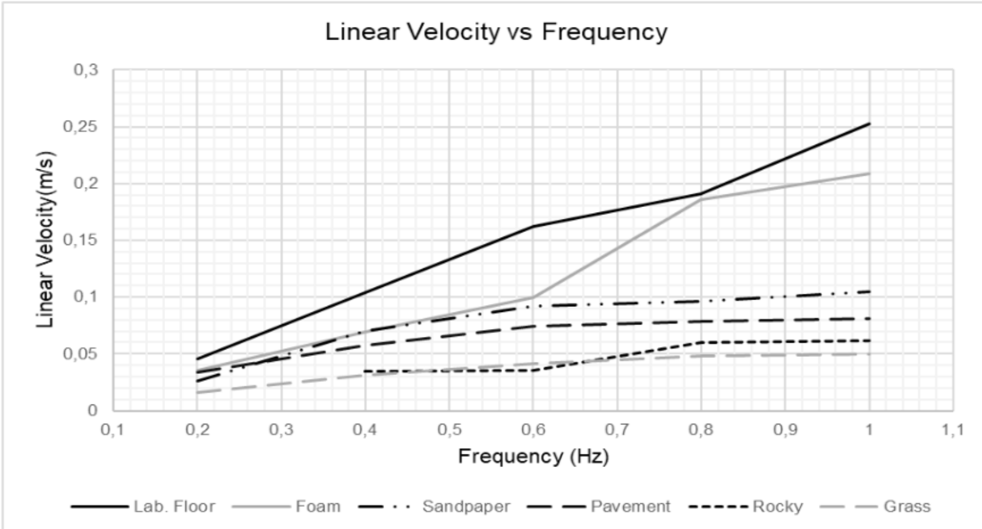

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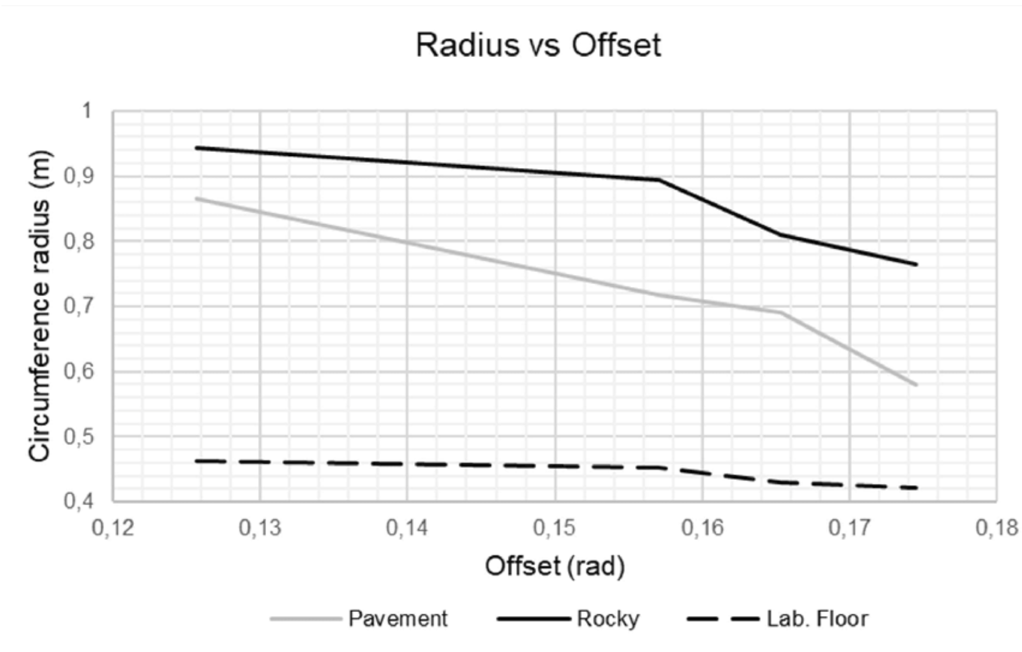
Figure 4: Relation between Circumference radius and Offset.



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6. Results of closed turn

The rotation tests were carried out on the same terrains as in the simple locomotion tests. The frequency was varied in the two simple sinusoidal generators (one per a diagonal pair of legs), and the angular velocity was measured. It was evident that the increased frequency resulted in an increase of the robot's angular velocity (Figure 5).

The maximum reached angular speed was 0.2443 rad/s. The level of firmness or friction on the structured terrains did not affect the displacement with intermediate frequencies (less than 0.8 Hz); however, the irregularity of the terrain did have an effect. Since the central rotation axes on these surfaces could be moved, the product of the ups and downs of the terrain affected the time it took the robot to turn. On the grass, the robot reached 19.74 % of the Lab Floor maximum angular speed.

7. Conclusion

Using composite sinusoidal generators proved to be beneficial for controlling modular robotic units in the absence of feedback. In particular, simple sinusoidal generators require a low computation cost, while allowing complex movements, by varying various control parameters (e.g. bias, frequency and amplitude) and changing the robot legs' protraction time.

The open turn is useful for going round intermediate-size obstacles on structured terrains and greater-sized obstacles on all types of surfaces. For turns with a radius smaller than 0.4225 m, it is necessary to combine successive closed turns and simple displacements. Rotation is the most effective method for changing the direction of locomotion.

The gaits for simple displacement and open rotation were successfully implemented using a bioinspired control approach. The use of this approach is limited by the Mecabot modular unit's processing, consumption and torque capacity. Hence, it is necessary to consider the trade-off between the cost and benefits of this strategy.

Integrating different types of sinusoidal generators, programmed in a decentralised way, allowed correct coordination and execution of the gaits for simple displacement, and open and closed turns on different terrains, thus complementing the research work on apodal (snake, caterpillar wheel) and hexapod configurations, improving the robot's adaptability.

Considering the decreased angular and linear velocities, and the increased turn radii due to the deviations caused by the ups and downs of terrains, future work should include developing methods for the robot coordination with feedback on the surface condition to improve the robot's performance.

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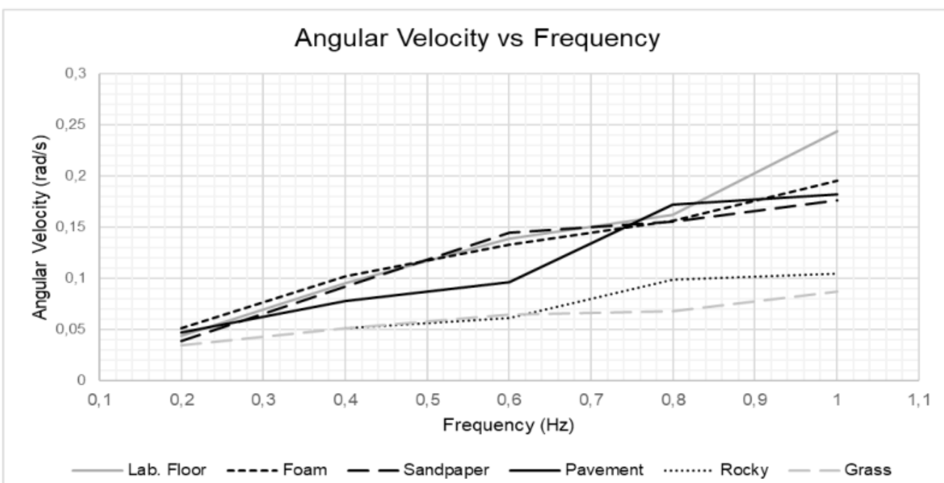
Figure 5: Relation between Angular Velocity and Frequency.



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