Robot skeleton design aimed at agricultural environment

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Robot skeleton design aimed at agricultural environment

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Abstract

This article brings the constructive aspects of a robotic structure that has mechanical characteristics inspired by vertebrate animals present in the agricultural environment or in similar landscapes. It is built in aluminum and has a design that allows its locomotion in soils with different textures. Each of the four legs is treated, in principle, uniquely and independently to allow a spherical area for the reason of having 4 degrees of freedom. Each of its rotational joints allows $180^\circ$ movement. The base is hexagonal to increase its contact area, balance its volume and allow it to float. The scope of this article starts from the formation of its bio-inspired structure and materials used and passes through direct and inverse kinematics, differential movements and speeds, static and dynamic analysis of forces that allowed us to conclude that, when it comes to terrains with heterogeneous textures, it is necessary expand the concept of agricultural robots to encompass their bio-inspired adaptability in animals living in agricultural cultivation areas and the like.
1 Introduction

The growth in demand for products from the agricultural activity is in line with the protection of the ecosystem, has demanded greater efficiency from producers [1]. Mechanics, electronics, and computing have been widely used in improving efficiency in agricultural activities, as well as reducing the cost of machinery, inputs, and labor. However, there is a great increase in the intensity of tasks in the field that has set the pace for the development of machines and implements [2].

All this tooling has received a lot of attention from the computing area, with the insertion of the Internet of Things (IoT) concept, corroborating to integrate all agricultural machinery, sensors, and geolocation devices with several other computational technologies, such as artificial intelligence, computer network, reality virtual and augmented, and so on [3].

It is important to consider that the texture of the soil and the compaction resulting from the tension on it, directly influence the development of the cultivated plant [4]. An important aspect to be considered is that, in areas of the high slope, such as those where mountain agriculture occurs, the requirements inherent to this characteristic are not met by conventional agricultural machinery [5]. Within this context, in areas with slopes above 35°, existing agricultural robots need to have their path carefully planned to avoid damage to equipment or even human beings present on the site [6].

A more careful look at living beings allows for mapping important physiological traits necessary for their survival. It is thanks to this adaptation that some species, including the European buffalo Bubalus murrensis has sustained itself after major climatic and environmental changes [7]. Another relevant aspect is observed in the morphological adaptive evolution of the locomotor skeleton of the Great Anolis lizards, which evolved within a subset of possible and highly accessible morphologies through genetic change [8].

The creation of artificial strategies has contributed to increased efficiency in agricultural production and allows proposing the development of a robotic, autonomous, a robust and efficient system, capable of providing the optimization of production and the maintenance of food and other products safety [9].

Although much has already been done to improve efficiency in agricultural production, there is still much to be developed in techniques and technologies for agricultural machinery and equipment. For this reason, the research starts from the hypothesis that a robotic structure that unifies aspects resulting from natural evolution, with those obtained artificially, can contribute to the formation of a robotic organism capable of adapting to different soil characteristics.
and, even so, being efficient in the application of agricultural inputs, such as fertilizers and pesticides.

As a means of corroborating this hypothesis, the study, and result of the abstraction of the morphological characteristics of buffaloes, lizards and dogs are presented, which allow them to move and transport loads, for the purpose of monitoring and acting on the dispersion of agricultural inputs in different terrains, with different textures and slopes, in a mobile robotic structure. This objective is justified by the great attention that robotic structures have received from academic and commercial circles, with their increasing presence in agricultural production environments, as well as the need to develop something capable of adapting to the environments where they will be used. The robot presented here was named ERACI (an acronym for articulated, autonomous, and adaptive robotic structure for image acquisition and classification in its written version in Portuguese) with aggregations compared to its first version, as [10].

2 Materials and Methods

To test the proposed hypothesis, it is considered that the contact area is inversely proportional to the pressure that is exerted on the soil and, depending on its magnitude, its rupture can result. For this reason, the density of the device should not be great, and its contact area should be maximized to reduce the likelihood that it will stick to the ground because of its texture. The design of its body is formed so that in the imminence of a water saturation or inundation, it can think floating in its ventral plane.

2.1 Geometric model

The design of the pseudo-body (Figure 1) is obtained through geometric analysis with the definition that its width, from end to end, should be equivalent to half of its length. To obtain it, it is first done on a checkered plane, with each of the quadrilaterals having a side equal to 1 unit (generic unit), a rectangle with 4 units wide and 10 units in length with a center congruent with that of the plane. The resulting rectangle is conceived as horizontal stabilizers in the back tailplane and the sagittal plane, and their connections take place at the vertices D, F, K, I, and D.

To ensure greater stability in the sagittal center, a line segment is drawn that forms the line $OP$. After that, the body axes are traced, which will receive each of the 4 legs at their external ends. From points G and L, straight lines are drawn to the closest upper and lower corners, crossing a diagonal of the quadrilateral outside the stabilization rectangle to form the lines $GH$, $GJ$, $LM$ and $LN$.

Still in Figure 1 B) the robot’s body is shown from a cross-plane perspective. It is possible to observe its hexagonal shape with the purpose of, in addition to allowing the accommodation of fluid containers and electrical
circuits, it also allows a better distribution of the pressure of the external elements and reducing the probability of loss of the equipment in a probable saturation water supply or flooding of the site. Its design is also based on geometric analysis. Thus, first, a line segment is drawn that cuts horizontally the checkered plane of 5 quadrilaterals in width and 6 in height of 1 unit each. Two points are defined, $C$ and $F$, about this segment $\frac{6}{5}$ unit from each end of $\overline{AB}$. From $\frac{5}{2}$ the segment $\overline{AB}$ a parallel segment is drawn $\overline{DE}$ and $\overline{GH}$, both above and below with a horizontal center equivalent to that of the line $\overline{AB}$. The two resulting lines have measures of 5 units each and their ends are then connected to points $C$ and $F$ to form the hexagon $CDEFHG$.

To obtain the measurements in each of the Links shown in Figure 2 the geometric methodology is used. In this one, the robot’s leg is drawn on a sheet with 4 stacked equilateral rectangles, with each frame 1 unit of the side. From point $D$, a straight line is drawn to the center of the quadrilateral (point $C$), from point $C$ to the upper left corner of the second quadrilateral (point $B$) and, finally, from point $B$, a straight line is drawn to the upper left corner of the fourth quadrilateral (point $A$). The line segment formed by points $A$ and $N$ is the length of joint $H$, perpendicular to the segments $\overline{HI}$. The perpendicular movement of the leg is provided by the pseudo-ilium which allows the entire structure of the leg to change its direction within a range of $180^\circ$. This technique was created and applied here to obtain proximity between the measurements of the locomotor structures of animals such as dogs, cattle and buffaloes, to ensure a degree of approximation between biological and artificial leg. A relevant aspect of this approach lies in the fact that the quadrature is used to determine the height and length of the device, inspired by the way dogs are classified in competitions, such as those organized by entities specialized in their breeding [11]. The last link is also inspired by the capacity of the buffalo carpus that allows a $180^\circ$, allowing this species can to escape quagmire with greater ease [12].
It was stipulated that the device must have its contact area distributed in 4 legs, with the Link refers to the last end parallel to the ground, to maximize the contact area of the device. Its shape should be within a square pattern, with its height and length of 0.6 m and its width of 0.3 m.

2.2 kinematics and dynamics models

The robotic system was developed to walk on 4 legs under the control of a computer system that will make its structure move or stand still in the balance. For this to be possible, it is necessary to raise its kinematic and dynamic models through algebraic calculations. Its study must start from the understanding that the base of the robot is its own body, from where each of the legs starts. Thus, this study is carried out with the understanding that both a robotic leg and a robotic arm are equivalent from a kinematic and dynamic point of view. Another situation is that, for this project, it is intended to position the end of Link 3 on the soil surface and not the end of the last Link (Link 4). However, it is understood that it is necessary to know the position of this last extremity.

2.2.1 Direct kinematic model

Direct kinematics allows knowing the position of a given end of a link about its base. Thus, based on the analysis of the structure, the values related to the convention of Denavit-Hartenberg (DH) 1.

Table 1 D-H Parameter table obtained by joint-to-joint analysis of the leg

<table>
<thead>
<tr>
<th>i</th>
<th>$\theta_i$</th>
<th>$d_i$</th>
<th>$a_i$</th>
<th>$\alpha_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\theta_1^*$</td>
<td>$d_1$</td>
<td>0</td>
<td>90$^\circ$</td>
</tr>
<tr>
<td>2</td>
<td>$\theta_2^*$</td>
<td>0</td>
<td>$l_2$</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>$\theta_3^*$</td>
<td>0</td>
<td>$l_3$</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>$\theta_4^*$</td>
<td>0</td>
<td>$l_4$</td>
<td>0</td>
</tr>
</tbody>
</table>
From this table, it is possible to obtain the homogeneous matrices for each device joint simply by applying equation 1.

The values obtained by the analysis are equivalent to those presented by [13] and [14]. Due to their similarity, each of the following transformations is also equivalent, however, with the kinematics performed not only for the last link but also for the extremity of the third link. Following the principles presented by these authors, the transformation matrix between each of the coordinates of the system is presented in (Equation 1), where $i = 1, 2, 3$ and 4.

\[
H_i^{-1} = \begin{bmatrix}
    \cos(\theta_i) - \sin(\theta_i) \cdot \cos(\alpha_i) & \sin(\theta_i) \cdot \sin(\alpha_i) & r_i \cdot \cos(\theta_i) \\
    \sin(\theta_i) \cdot \cos(\alpha_i) & -\cos(\theta_i) \cdot \sin(\alpha_i) & r_i \cdot \sin(\theta_i) \\
    0 & \cos(\alpha_i) & d_i
\end{bmatrix} (1)
\]

Since it is necessary to adapt the device to different environments, transformations are carried out to allow each of the extremities that make up each leg to be known. This is a strategy that will help the robot to get around and adapt to different landscapes and soil textures.

To make the visualization of Equations 2 and 5 simpler, descriptions of their sin and cos are described as: $\cos(\theta_2 + \theta_3) = C_{23}$, $\sin(\theta_2 + \theta_3) = S_{23}$, $\cos(\theta_2 + \theta_3 + \theta_4) = C_{234}$ and $\sin(\theta_2 + \theta_3 + \theta_4) = S_{234}$.

\[
T_0^1 = \begin{bmatrix} C_1 & S_1 & 0 \\ S_1 & -C_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} (2)
\]

\[
T_0^2 = T_0^1 \times T_1^1 = \begin{bmatrix} C_1C_2 & -C_1S_2 & S_1 & l_2C_1C_2 \\ C_1S_2 & -C_1C_2 & S_1 & l_2S_1C_2 \\ S_2 & C_2 & 0 & l_2S_2 + d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} (3)
\]

\[
T_0^3 = T_0^1 \times T_1^1 \times T_2^1 = \begin{bmatrix} C_1C_2 & -C_1S_2 & S_1 & C_1(l_2C_2 + l_3C_23) \\ C_1S_2 & C_1C_2 & S_1 & C_1(l_2S_2 + l_3C_23) \\ S_2 & C_2 & 0 & l_2S_2 + l_3S_23 + d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} (4)
\]

\[
T_0^4 = T_0^1 \times T_2^1 \times T_3^1 = \begin{bmatrix} C_1C_{234} & -C_1S_{234} & S_1 & C_1(l_2C_2 + l_3C_{23} + l_4C_{234}) \\ C_1S_{234} & C_1C_{234} & S_1 & C_1(l_2S_2 + l_3C_{23} + l_4C_{234}) \\ S_{234} & C_{234} & 0 & l_2S_2 + l_3S_{23} + l_4S_{234} + d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} (5)
\]
2.2.2 Inverse kinematic model

To obtain the inverse kinematics of each of the robot’s legs, the analytical-geometric method is used. Like forward kinematics, inverse kinematics is equivalent to those presented by [14] and [13] that graphically present this decomposition. With this, the articulatory system of the leg is decomposed into two parts. One corresponds to the movement provided by Joint 1 in which the angle \( \theta_1 \) determines the positioning of the lower end of the leg on the axes \((X,Y)\) and the other that considers an axis \( R \), fixed at a point called \( p_R \) determined by applying the Pythagorean Theorem, from these axes. The angle \( \theta_1 \) and the point \( p_R \) are determined by the equations 6 and 7, respectively.

\[
\theta_1 = \arctan\left(\frac{p_Y}{p_X}\right),
\]

\[
\theta_1 = \begin{cases} 
\theta_1, & 0^\circ \leq \theta_1 \leq 90^\circ \\
\theta_1 + 180^\circ, & \theta_1 > 90^\circ 
\end{cases}
\] (6)

\[
r_4 = R = \sqrt{X^2 + Y^2}
\] (7)

\[
z_4 = Z - d_1
\] (8)

\[
p_R = \sqrt{P_x^2 + P_y^2}
\] (9)

\[
r_3 = r_4 - l_4 \cdot \cos(\phi)
\] (10)

\[
z_3 = z_4 - l_4 \cdot \sin(\phi)
\] (11)

\[
\phi = \arctan\left(\frac{z_4}{r_4}\right)
\] (12)

\[
\psi = \arctan\left(z_3/r_3\right)
\] (13)

\[
\beta = \arccos\left(\frac{p_R^2 + l_2^2 - l_3^2}{2 \cdot p_R \cdot l_2}\right)
\] (14)

\[
\theta_2 = -(\beta - \psi)
\] (15)

\[
\theta_2' = \beta + \psi
\] (16)

\[
\theta_3 = -(\arccos\left(\frac{l_2^2 + l_3^2 - pR^2}{2 \cdot l_2 \cdot l_3}\right) - 180^\circ)
\] (17)

\[
\theta_3' = (\arccos\left(\frac{l_2^2 + l_3^2 - pR^2}{2 \cdot l_2 \cdot l_3}\right) + 180^\circ)
\] (18)

\[
\theta_4 = -(\phi - (\theta_2 + \theta_3))
\] (19)
The equations 16 and 18 determine the elbow down and must be used together, in the same way, equations 15 and 17 define the elbow up and should also be used together. The management of these possibilities is carried out by the control system that will be dealt with in another article.

2.2.3 Differential and static kinematic model

Differential kinematics relates the velocities and accelerations of the components of the kinematic chain, resulting in a total velocity and acceleration at the end of the system [15].

Its estimation can be obtained through iterations over the forward kinematics equations. In this way, the homogeneous matrix of the joint analyzed is first obtained through Equation 20, with \( i = 1, 2, 3 \) and 4. The equations described here for the angular velocity (\( \omega \)) and linear velocity (\( v \)) are based on [16] and adapted to the purpose of the project and the simulation in Matlab software [17].

\[
H_{i-1}^i = R_{z,\theta_i} \cdot T_{z,d_i} \cdot R_{x,\alpha_i} \cdot T_{x,l_i} \tag{20}
\]

Where,

\[
R_{z,\theta_i} = \begin{bmatrix}
\cos(\theta_i) & -\sin(\theta_i) & 0 & 0 \\
\sin(\theta_i) & \cos(\theta_i) & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix} \tag{21}
\]

\[
T_{z,d_i} = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & d_i \\
0 & 0 & 0 & 1
\end{bmatrix} \tag{22}
\]

\[
R_{x,\alpha_i} = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos(\theta_i) & -\sin(\theta_i) & 0 \\
0 & \sin(\theta_i) & \cos(\theta_i) & 0 \\
0 & 0 & 0 & 0
\end{bmatrix} \tag{23}
\]

\[
T_{x,l_i} = \begin{bmatrix}
1 & 0 & 0 & l_i \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \tag{24}
\]

The result of applying Equation 20 is similar to obtaining homogeneous matrices based on Equation 1.

At the base, an identity matrix is considered a homogeneous matrix, since in it there should be no rotation or translation movement, as it is a fixed point on the device in relation to each of the parts of the leg.

After obtaining this matrix, the angular velocity survey is carried out (\( \omega \)) through Equation 25.

\[
\omega_i^i = R_{i-1}^i \cdot \omega_{i-1}^{i-1} + \dot{\theta}_i \cdot \dot{Z}_i \tag{25}
\]
Where in the first iteration $\omega_{i-1}^i$ equals $[0 0 0]^T$, $R_{i-1}^i = H_{i-1}^{i-1}(1 : 3, 1 : 3)^T$ and $\dot{\theta}_i = H_{i-1}^{i-1}(1 : 3, 3)$.

Then, the linear velocity $v$ relative to the joint in question is obtained through Equation 26.

$$v_i^i = R_{i-1}^i \cdot (v_{i-1}^i + W_{i-1}^i \times O_{i-1}^i) \quad (26)$$

Where in the first iteration $v_{i-1}^i$ equals $[0 0 0]^T$, $R_{i-1}^i = H_{i-1}^{i-1}(1 : 3, 1 : 3)^T$ and $O_{i-1}^i = H_{i-1}^{i-1}(1 : 3, 4)$.

After obtaining the angular and linear velocities, it is possible to obtain the Jacobine Matrix, which is nothing more than the mapping of velocity in joint space to velocities in Cartesian space. It is not invertible at singularities, where the determinant is 0. When the robotic leg is in a singular position, it loses one or more degrees of freedom in Cartesian space.

This mapping is described by a Jacobian matrix that depends on the handler configuration. It is expressed with the same representation and operational space obtained by differentiating direct kinematics. It defines the dynamic relationship between the different Coordinate systems [18].

The Jacobian for the structure is given in the Equations from 27 to 34.

$$J = \left[\begin{array}{c} Z_0 \times (p_4 - p_0) \\ Z_0 \times (p_4 - p_1) \\ Z_2 \times (p_4 - p_2) \\ Z_3 \times (p_4 - p_3) \end{array}\right]$$ \quad (27)

$$p_0 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$ \quad (28)

$$p_1 = \begin{bmatrix} 0 \\ 0 \\ d_1 \end{bmatrix}$$ \quad (29)

$$p_2 = \begin{bmatrix} l_2 C_1 C_2 \\ l_2 S_1 C_2 \\ l_2 S_2 + d_1 \end{bmatrix}$$ \quad (30)

$$p_3 = \begin{bmatrix} C_1 (l_2 C_2 + l_3 C_{23}) \\ S_1 (l_2 C_2 + l_3 C_{23}) \\ l_2 S_2 + l_3 S_{23} + d_1 \end{bmatrix}$$ \quad (31)

$$p_4 = \begin{bmatrix} C_1 (l_2 C_2 + l_3 C_{23} + l_4 C_{234}) \\ S_1 (l_2 C_2 + l_3 C_{23} + l_4 C_{234}) \\ l_2 S_2 + l_3 S_{23} + l_4 S_{234} + d_1 \end{bmatrix}$$ \quad (32)

$$z_0 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$ \quad (33)
When the robot moves on each of its legs, it is supporting its weight and it is necessary to make mathematical considerations about this process. One of the ways that can be used to solve this problem is the use of the concept of static equilibrium, which deals with the torque values needed in the joints for this purpose. To obtain it, all the joints are locked and then the force-moment description of the joints is carried out to the reference system of each link. The result of this is the equations that model the set of torques necessary to sustain a static load acting on the effector \[16\]. The equations for this are based on the methods of \([16]\) and its calculation is performed iteratively from the tip of the leg, in other words, in the last link of the robot, which interacts directly with the ground or any other medium. Thus, the first task is to obtain the homogeneous matrix relative to the link through Equation \(20\). Then the Force acting on it is calculated using the Equation \(35\). In the case of ERACI \([10]\), the force acting on it is equivalent to the weight of the robotic device itself, as defined by Newton’s Third Law.

\[
f_i^j = R_{i+1}^i \cdot f_{i+1}^{i+j} \tag{35}\]

Where, \(R_{i+1}^i = H_i^{-1}(1 : 3, 1 : 3)\) and \(H_i^{-1}\) is given with respect to Equation \(20\) and \(f_{i+1}^{i+j}\) is the force applied to this last link given by its vector form \([fx fy fz]\).

Then the moment for the same link is calculated, according to Equation \(36\).

\[
n_i^j = R_{i+1}^i \cdot n_{i+1}^i + O_{i+1}^i \times f_{i+1}^i \tag{36}\]

Where, \(n_{i+1}^i\) in the first iteration is \([0 0 0]^T\) and \(O_{i+1}^i = H_i^{-1}(1 : 3, 4)\). Finally, the static torque for the link in question is given by Equation \(37\).

\[
\tau_i = n_i^i \cdot \hat{Z}_i^i \tag{37}\]

Where, \(\hat{Z}_i^i = H_i^{-1}(1 : 3, 3)\).

### 2.2.4 Dynamic model

Dynamical systems are those in which behavior evolves over time, their physical properties, such as mass or inertia, remain constant and their behavior can change depending on what happens around them \([19]\).

For the device, the gravitational acceleration force \(g\) is given as \(G = [gx \ gy \ gz]\), for the magnitude of how it acts on it depends on the orientation of the device to the space in which it finds itself.

To obtain this model, it is necessary to distinguish between the homogeneous matrix as a function of the Links and the matrix relative to each of the joints. With this, Equation is used \(20\) in two different ways, in which the D-H table is changed to highlight each of the centers of mass in each link \(2\).
Table 2  D-H Parameter table obtained by analyzing the link-to-link center of mass of a leg

<table>
<thead>
<tr>
<th>i</th>
<th>$\theta_i$</th>
<th>$d_i$</th>
<th>$a_i$</th>
<th>$\alpha_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\theta_1^*$</td>
<td>0</td>
<td>0</td>
<td>90°</td>
</tr>
<tr>
<td>2</td>
<td>$\theta_2^*$</td>
<td>$d_1c$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>$\theta_3^*$</td>
<td>0</td>
<td>$l_2c$</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>$\theta_4^*$</td>
<td>0</td>
<td>$l_3c$</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>$l_4c$</td>
<td>0</td>
</tr>
</tbody>
</table>

The equations described here are also based on [16] and adapted to the purpose of the project and the simulation in Matlab software [17].

It is important to note that the iterations occur in a number equivalent to that described in Table 1 for the joints, that is, in the case of ERACI it occurs for 4 cycles corresponding to joints 1, 2, 3, and 4. Another important piece of information is that the homogeneous matrices are called here as $HEJ_i$ for the domain of joints and $HEE_i$ ($i = 1, 2, 3$, and 4 in the first part and $i = 4, 3, 2$, and 1 in the second part) for the domain of the links and their respective centers of mass. The iterations occur in two distinct parts, the first from the first link to the last, and the second part from the last link to the first.

After obtaining the homogeneous matrices, Equation is used 25, passing as parameter H the array $HEJ_i$. Then the angular acceleration is obtained $(\ddot{\omega}_{i+1}^j)$ of the current link, through Equation 38.

$$\ddot{\omega}_{i+1}^j = R_{i+1}^i \cdot \dot{\omega}_i^j + R_{i+1}^i \cdot \dot{\theta}_i \cdot \dot{Z}_{i+1} + \ddot{\theta}_{i+1} \cdot \dot{Z}_{i+1}^j$$  (38)

Where, $R_{i+1}^i = HEJ_i^{-1}(1:3,1:3)^T$, $\omega_i^j = [0 0 0]$in the first iteration, $\dot{\theta}_i$ is the speed delivered to the joint by the torque motor, $\dot{Z}_{i+1} = HEJ_i^{-1}(1:3,3)^T$ and $\ddot{\theta}_{i+1}$ is the acceleration delivered to the joint by the torque motor.

The next step within this iteration is to obtain the linear acceleration $\dot{v}$ through Equation 39.

$$\dot{v}_{i+1}^{j+1} = R_{i+1}^i \cdot (\omega_i^j \times O_{i+1}^j + \omega_i^j \times (\omega_i^j \times O_{i+1}^j) + \dot{v}_i^j)$$  (39)

Where, $R_{i+1}^i = HEJ_i^{-1}(1:3,1:3)^T$, $O_{i+1}^j = HEJ_i^{-1}(1:3,4)$, $\dot{v}_i^j = [g_x g_y g_z]$ and $g_x$, $g_y$ and $g_z$ is the acceleration of gravity decomposed, according to the orientation of the device in the plane.

The linear velocity at the center of mass is calculated using Equation 40.

$$\dot{v}_{i+1}^{j+1} = \dot{\omega}_{i+1}^j \times O_{i+1}^{j+1} + \omega_{i+1}^{j+1} \times (\omega_{i+1}^{j+1} \times O_{i+1}^{j+1}) + \dot{v}_{i+1}^{j+1}$$  (40)

Where, $O_{i+1}^{j+1} = HEE_i^{-1}(1:3,4)$.

The next steps in the first part for acquiring the kinematic model are the calculations of force (F) and moment (N) for each of the joints. Its algebraic formulation is presented through Equations 41 and 42.

$$F_{i+1}^{j+1} = m_{i+1} \cdot \dot{v}_{i+1}^{j+1}$$  (41)

Where m is the mass of the link being iterated at the moment.
\[ N_{i+1}^{i+1} = I_{i+1}^{i+1} \cdot \dot{\omega}_{i+1}^{i+1} + \omega_{i+1}^{i+1} \times I_{i+1}^{i+1} \cdot \dot{\omega}_{i+1}^{i+1} \]  

\[ I_{i+1}^{i+1} \] is the inertia tensor relative to the center of mass (Equation 43) of the link being analyzed in the iteration. It is a symmetric matrix \(3 \times 3\), that is, its conventional form is equal to its transposed form.

\[
I_p = \begin{bmatrix}
I_{xx} & -I_{xy} & -I_{xz} \\
-I_{xy} & I_{yy} & -I_{yz} \\
-I_{xz} & -I_{yz} & I_{zz}
\end{bmatrix}
\]  

(43)

The values for each of the elements of the Matrix are obtained computationally. Because it is considered about the center of mass, the elements \(I_{xy} = I_{yx}\), \(I_{xz} = I_{zx}\) and \(I_{yz} = I_{zy}\) = 0. The others are: \(I_{xx} = \frac{m_1}{12} \cdot (h^2 + l^2)\), \(I_{yy} = \frac{m_1}{12} \cdot (w^2 + h^2)\) and \(I_{zz} = \frac{m_1}{12} \cdot (l^2 + w^2)\).

At the end of each iteration, the resulting vectors for Force (F) and Moment (N) are stored in a list with an index equivalent to the result of the iteration it represents. These vectors will be the input for the functions inherent to the second part of the algorithm that is performed from outside to inside the system.

At the end of all iterations of the first part, that is, the part that performs the application of equations from the inside to the outside, the second part is performed, from the outside to the inside.

First, the homogeneous matrices are obtained \(HEJ\) and \(HEE\) for the current joint. Then the resultant force on the iterated link is calculated using Equation 44.

\[
f_i^i = R_i^{i+1} \cdot f_{i+1}^{i+1} + F_i^i
\]  

(44)

Where, \(R_i^{i+1} = HEJ_i^{-1}(1 : 3, 1 : 3)\), \(f_{i+1}^{i+1} = [0 0 0]^T\) in the first iteration and \(F_i^i\) is the force stored in the list of forces obtained during the calculation of forces in the first part (from inside to outside), and its obtainment requires the search for the index equivalent to the current iteration.

The moment is calculated by applying Equation 45.

\[
n_i^i = N_i^i + R_i^{i+1} \cdot n_{i+1}^{i+1} + O_{ci}^i \times F_i^i + O_{i+1}^i \times R_i^{i+1} \cdot f_{i+1}^{i+1}
\]  

(45)

\(N_i^i\) is obtained from the index, equivalent to the current iteration, in the list of moments calculated and stored in the first part; \(R_i^{i+1} = HEJ_i^{-1}(1 : 3, 1 : 3)\), \(n_{i+1}^{i+1} = [0 0 0]^T\) on the first iteration, \(O_{ci}^i = HEE_i^{-1}(1 : 3, 4)\), \(F_i^i\) is the same used in Equation 44 and \(O_{i+1}^i HEJ_i^{-1}(1 : 3, 1 : 3)\).

The final torque at each of the joints is obtained by Equation 46.

\[
\tau_i = (n_i^i)^T \cdot \dot{Z}_i^i
\]  

(46)

The equations so far allow the robotic system to be modeled, considering each leg individually and the elucidation of the torque capacity required for each servo motor.
3 Results and Discussion

From the presented methodologies, the CAD models were created using the FreeCad software [20] which manages geometric and algebraic simulation with GeoGebra software [21] and the construction of the physical device. The result of these models are shown in Figure 3.

Based on the methodology presented for the design of the structure and the CAD model presented, the materials for the construction of the prototype were chosen. After analyzing the various existing possibilities, aluminum was chosen for this purpose due to its lightness, strength, and malleability. In this construction, pairs of bars of this metal were used, connected by rivets, with spacing stabilized by a cylindrical artifact in PVC plastic (Polyvinyl Chloride). Non-definitive fixations were performed with steel screws. The joints were made using two zinscs bearing macaques and a 0.06 m M8 steel screw shafts.

The final result for the physical structure of the metal device is shown in Figure 4.
In Table 3 the total partial weight is equivalent to the entire structure considering only one leg and the body. To obtain the total weight of the structure, considering the 4 legs and the body, the weight of each of the parts that compose it must be multiplied by 4, which will result in a total weight of the structure of 2.687 Kg. However, it must be considered that this weight refers to the robot’s skeleton, without its protective layers, circuits, sources and 2 containers of chemical products that it must carry for application in the fields. These values are important to model the dynamics of the system and allow an inference of the torques necessary for its movement to be made.

As mentioned before, it was possible to create a geometric model for simulating the application of direct and inverse kinematics, obtained through the
equations presented in the methodologies section and the kinematic model subsection.

The simulations from here consider that all 4 legs must have an equivalent kinematic and dynamic behavior with their integration. Synchronization should be addressed in a later study that relates all models built here with the device’s control system. Thus, it was first modeled in GeoGebra software [21] as a leg to be controlled by changing the angular positioning of its joints when it comes to evaluating forward kinematics and according to the position specification of the end of its last link when dealing with inverse kinematics. Another relevant issue is that studies on kinematics lead to a more succinct understanding that the simulation approach of a robotic leg is equivalent to that of a robotic arm because in both, the inertia reference of the device is the basis of the robot. In the case of ERACI, the structure may be in motion, however, for its legs, the base is still fixed and allows the mapping of the space about it, through its connection to the first link and its first joint. Figure 5 shows the direct kinematics simulation window in the GeoGebra software.

![Fig. 5](image-url) Windows for simulating the direct kinematics of the ERACI robotic leg in the GeoGebra software. A) shows the algebraic values used for the simulation; B) displays the sliders relative to the angles that can for the ERACI fluctuate between -90° and 90°; C) is the 3-dimensional viewing window of the movements performed by the leg about the angles determined in the sliders

For the simulation of direct kinematics with GeoGebra, it was necessary to create sliding controls to represent each of the joints existing in each of the legs, and they were named as $\theta_1$, $\theta_2$, $\theta_3$ and $\theta_4$. Afterward, the equations related to the positioning of each of the links were described and named as $A_{1234} = T_{0}^{4}$, $A_{123} = T_{0}^{3}$, $A_{12} = T_{0}^{2}$, and $A_{1} = T_{0}^{1}$; these names refer to each of the homogeneous transformations presented in the methodology section that deals with direct kinematics. With this simulation, it was possible to verify the validity of the obtained homogeneous transforms and thus ensure that their use in a real system is successful.

Another simulation performed also in GeoGebra allows validating the algebraic models of inverse kinematics. In this simulation, it is possible to
determine a point in space and let the equations determine what angle the joints must have to reach it. The screen for this task is shown in Figure 6.

As for the simulation of direct kinematics, it was necessary to create 3 sliding controls, one for each Cartesian coordinate (px, py, and pz). After creating these controls, the algebraic equations obtained in the inverse kinematics section in the methodology section were stored in variables in the software and, there named as $\epsilon$, $\phi$, $\theta_{1+}$, $\theta_{2+}$, $\theta_{3+}$ and $\theta_{4+}$. The + sign in each of them refers to which sign resulting from a square root is used $\pm \sqrt{x}$. As a result of the simulation, the parts where singularities occur are perceived, in other words, when the model cannot position the end of the last link at the desired point because no angle allows it. Based on this, it is understood that when developing the robot control system, these issues must be considered and, strategies to avoid errors must be implemented.

In addition to the simulations performed with GeoGebra, simulations were also performed in Matlab [17]. They have the purpose of allowing the visualization of the system in operation under the application of a sinusoidal signal that varies from $-\frac{\pi}{2}$ and $\frac{\pi}{2}$ rad (radians) at a fixed frequency of 0.43633213 rad/s. Therefore, it does not enter the question of control to be addressed in another article. With this simulation, it is possible to visualize aspects such as angular and linear velocity in the last link of the robotic leg. It is also the purpose of this simulation to visualize the static and dynamic torques for each of the joints at different moments in time due to the movements performed by each of the joints.

For this to be possible, the equations inherent to the differential, static and dynamic models were calculated and transformed into computational functions to be executed in Simulink which, in turn, was configured to receive values referring to forces, masses, velocities and accelerations. The velocity is derived from the block that generates the sinusoidal signal inherent to the joint position.
variation, and the acceleration is derived from this same velocity. This is done by tapping blocks added to the output of the daisy chain signal generator. In functions where position, velocity, and acceleration are input, this value is passed in all inputs, that is, it is assumed that $\dot{\theta}_1 = \dot{\theta}_2 = \dot{\theta}_3 = \dot{\theta}_4 = \ddot{\theta}$ for positioning, $\ddot{\theta}_1 = \ddot{\theta}_2 = \ddot{\theta}_3 = \ddot{\theta}_4 = \ddot{\theta}$ for speed and $\dddot{\theta}_1 = \dddot{\theta}_2 = \dddot{\theta}_3 = \dddot{\theta}_4 = \dddot{\theta}$. The Figure 7.

![Figure 7](image)

**Fig. 7** Windows for simulating static and dynamic speed and torque models

The simulation requires that some constant values are previously determined, such as the length of the links, their masses, and the mass of the load supported by the device. For this, the values were defined as:

- length of each of the links in meters ($l_1, l_2, l_3, l_4$) : $L = [0.1 \ 0.3 \ 0.21 \ 0.9]$;
- length of each of the links to the center of mass in meters ($lc_1, lc_2, lc_3, lc_4$) : $LCM = L$;
- mass of each of the links in kilograms ($m_1, m_2, m_3, m_4$) : $M = [0.094 \ 0.146 \ 0.094 \ 0.02]$;
- mass of the load supported by the device in kilograms : $m = 10$;
- acceleration of gravity perceived by the device in meters per second square : $G = [0 \ 0 \ 9.8]$;
- inertia tensor for link 1 : $I_1 = 1.0 \times 10^{-6} \cdot \begin{bmatrix} 97.920 & 0 & 0 \\ 0 & 22.410 & 0 \\ 0 & 0 & 81.160 \end{bmatrix}$ (47)
- inertia tensor for link 2 : $I_2 = 1.0 \times 10^{-3} \cdot \begin{bmatrix} 1.130 & 0 & 0 \\ 0 & 0.040 & 0 \\ 0 & 0 & 1.100 \end{bmatrix}$ (48)
Inertia tensor for link 3:

\[ I_3 = 1.0 \times 10^{-6} \begin{bmatrix} 365.030 & 0 & 0 \\ 0 & 22.410 & 0 \\ 0 & 0 & 348.280 \end{bmatrix} \] (49)

Inertia tensor for link 4:

\[ I_4 = 1.0 \times 10^{-3} \begin{bmatrix} 1.350 & 0 & 0 \\ 0 & 0.008 & 0 \\ 0 & 0 & 1.351 \end{bmatrix} \] (50)

The values for each of the inertia tensors were obtained by the model already presented and discussed in Equation 43 and subsequent explanation.

After building the simulation bench and determining the input values, the simulation was performed and presented the values shown in Figure 8.

The graphs show the evolution of each of the quantities as a function of time during the 60 seconds. In Figure 8 A) it is possible to see that the speed in the last link of the chain system oscillates between 0.5 and 2.0 radians per second. This is because its velocity is a result of the velocities of other joints that participate in the current movement. Because all angles have the same value, this is characterized as a movement of retraction and extension of the leg, with all joints acting together for this. The Figure 8 B) shows the graph dealing with the linear velocity at the end of the last joint, given here in meters per second. Their values oscillate, for the same reasons presented in (A) between 0.5 and 2.5 m/s.
Figures 8 C) and D) present the magnitudes of the torques in Newton-meters (N.m) required to maintain the system in static and dynamic equilibrium, respectively. An analysis of A) shows that during a full contraction and extension activity, the torques at the joints $\theta_1$ and $\theta_2$ are identical with variations between 110.0 and 140.0 N.m. The torques $\theta_3$ and $\theta_4$ are constants with values of 90.0 and 110.0 N.m, respectively. This is due to the dimension of the movement that these links need to perform to contract or expand. In B) which considers the dynamics of the system, the torque oscillations are quite exuberant compared to the static model. The values for the $\theta_1$ have a maximum peak of 0.75 N.m, $\theta_2$ of 2.0 N.m, $\theta_3$ of 0.75 N.m and $\theta_4$ of 0.3 N.m. The presentation of the values for the dynamic torques remind us that the control system must act so that there is no greater effort than the servomotor is capable of withstanding and, for that, in a quadruped robot like the ERACI it is essential so that it does not overload due to the excessive accumulation of all its mass on only one of the legs. In all situations where it is possible to visualize negative values for torque, there is the idea that the joint takes advantage of external forces, such as the force of gravity, to perform the movement.

It is important to emphasize that the simulations presented so far are carried out for the construction and equation of the structure. Its verification in the field will be analyzed in a next article that will deal with the construction of the control system.

4 Conclusion

Robotic devices have been of great importance for performing tasks that require precision and repeatability. This resource has gained space in several segments of human activities, such as industry, entertainment, exploration activities on this and other planets, and in agriculture. This integration between these different segments with the evolution of robotics has shown great efficiency and provided the evolution of related studies. Especially in agricultural activity, there are many of adaptations of robotics in various machinery and equipment.

Thus, this research work sought to present an alternative based on the evaluation of the evolution of the vertebral structures of animals for the manufacture of a device with the purpose that it can be used in different types of agricultural or similar environments.

To reduce the production costs of the prototype, some strategies were taken, without compromising its versatility, durability, and lightness. This resulted in the making of a prototype of the device’s skeleton in aluminum and the use of a link called the ilium at the ends of the base, orthogonal to the remaining links: femur, shin, and foot.

The use of software for algebraic and geometric purposes, such as GeoGebra and MATLAB, allowed the realization of several tests that validated the structure and its mathematical formulations for kinematics and dynamics.
Finally, it is understood that the development of a control system that implements the mathematical models described so far and allow the testing of the physical structure in the environment for which it is intended is justified.

Declarations

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Conflicts of interest/Competing interests
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Code or data availability
The project had the use of FreeCad software for design, Geogebra and Matlab for simulation. Both softwares duly referenced in the text. The simulation and design files are available as a supplementary zip file.

References


Robot skeleton design aimed at agricultural environment


Robot skeleton design aimed at agricultural environment


