Kinematic Model for Robotic Terrestrial Locomotion Inspired in Doves (Columbia livia)

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Abstract

Objectives: In this work we create and implement a terrestrial locomotion model inspired in Dove waking scheme and Craig nomenclature for biped robot movement design. Methods: For the model implementation we use the Craig method to obtain the transformation matrix that describes position and orientation of leg joints in Doves. We obtain biological experimental results in a group of Doves (Columbia livia) in order to contrast and complement previous work in terms of energy efficiency. Findings: We propose kinematic models for slow and moderate pace, which were evaluated through energy efficiency analysis. Application: The model offers an alternative for design of mobile robots where the locomotion is performed in irregular terrains since the biped model proposed here, has just two discrete support points in comparison with other types of locomotion such as wheels.

Keywords: Biped Locomotion, Biped Robotic, Bio-mechanical Motion, Craig Nomenclature, Denavit Hartenberg

1. Introduction

The terrestrial robot locomotion is a relevant topic of research since it is one of the most determinant aspects to be considered for a suitable remote task execution. In this sense, wheels locomotion has widely studied and implemented since it offers advantages such as less energy consumption, stability and less modeling complexity. However, its implementation in non-uniform terrains generates wheel sliding and velocity reduction that require an increase of energy cost for robots or improvements in mechanical designs to enhance wheels traction1. In this regard, biped inspired locomotion offers an alternative that emulates the legs movement of humans and birds, allowing the movement in spite of the terrain irregularities2. In this approach we focus on bird inspired locomotion since in comparison with humans, which base their movement in two segments (femur and tibia) and three joints (hips, knees y ankle), they have developed a more complete and sophisticated motion scheme through three segments (femur, tibiotarsus and tarsometatarsus) and four joints (hips, knees, ankle and foot). This can be shown in Figure 1.

In this work, we develop a kinematic model based on the Craig nomenclature and biological experiments made in a group of Doves (Columbia livia). This model offers a design tool inspired in bird terrestrial motion that can be used for locomotion in robots, which, to the best of our knowledge, have not been discussed in literature. The rest of this article is organized as follows. In Section 2 we describe the most relevant work related to bird movement analysis, kinematic models and bio-inspired robots. Section 3 describes the main concepts related to

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the model implementation. In section 4 we describe the implemented model in a detailed way. Finally, in Sections 5 and 6 we show the results analysis and the conclusions, respectively. In order to describe the terrestrial bird behavior, mathematic models have been complemented with experimental data obtained through multiple acquisition methods. In this sense, the Doves courtship is studied through visual data acquisition and a learning algorithm based on neuronal networks. The implemented model quantifies the head balancing and predicts unable information to minimize the free energy. Additionally, those results are confirm about the patterns in locomotion sequences, both for normal and courtship cycles. A kinematic model is developed using metallic spheres located in strategic points in the body of a quail. Through x-ray and video camera they construct a 3-D description for the bird movement. Between the most important findings are the center of mass localization along with the fact that the stability is improved using a flexed position. Additionally, they show that the modified convention of the Denavit-Hartenberg parameters is suitable for the kinematic description of open and close loop structures and to define the z axis as the articulation axis. On the other hand, the simulation results show that the implemented model is suitable to replicate biped locomotion and can be implemented as a human model.

2. Preliminaries

In this section we describe relevant concepts used to define the locomotion model of our approach. First, in Section 3.1 we describe general aspects about bird locomotion. Second, in Section 3.2 we show energy and mechanical concepts related to this type of locomotion. Finally, a description about the characteristics for the selected Dove (Columba livia) is given.

2.1 General Aspects about Bird Locomotion

The bird locomotion cycle begins when a foot has ground contact and ends when the same foot touches the floor again. This can be shown in Figure 2. The foot support period is the phase at which a foot is on the floor. This is divided in single and double support. In the single support state, only one foot is working as body support for the bird body. In double support, both feet are supporting the bird body at the same time (the absence of a double foot support period differentiates walking and running movements). The foot balancing period is the phase at which the foot is not on the floor.
The step length is the lineal distance over the progression plane between the point at which a foot heel touches the floor and the other foot.

Complete step length is the lineal distance over progression plane between the points at which a foot heel touches the floor two times (Figure 3).

A detailed description of the locomotion period shown in Figure 2 is given in Figure 4. Observe how the foot support period takes 60% of it (40% in single support and 20% in double support), and the balancing period takes the remaining 40%.

2.2 Relevant Concepts about Mechanic and Energy for Locomotion

A locomotion scheme is defined through Kinematic and Dynamic models in order to describe joints movements and the required energy. Generally, the mathematical model for locomotion combines the translational and rotational movement of the kinematic chain, i.e., the set of links (bones) connected to each other. This chain can be opened, when only one foot is on the floor (e.g. balancing period), or closed, when both feet are on the floor (e.g. double support period). This means that for a biped model inspired in birds, we have 6 rotational joints (3 for each leg), each one with 3 degrees of freedom when the leg is configured as an open kinematic chain.

2.3 Kinematic and Dynamic Models

A kinematic model is based on transformations between reference systems related to the variables representing joints and their spatial location. It considers the movement description through position, velocity, acceleration and the four quantities related to each joint as is model,

\[ t_1 = \begin{pmatrix} a_{i-1} & \cos \theta_i & \alpha_i & \sin \theta_i \\ 0 & \cos \alpha_i & -\sin \alpha_i & \sin \alpha_i a_{i-1} \\ 0 & \sin \alpha_i & \cos \alpha_i & \sin \alpha_i d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \]

which, can be expressed in more detail using (2), where the four quantities established in are included:

\[ t_1 = \begin{pmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_i & -s\alpha_i a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & c\alpha_i & c\alpha_i a_{i-1} \\ 0 & 0 & 0 & 1 \end{pmatrix} \]

The complex transformation matrix can be obtain from the last matrix with the objective of build the direct kinematic, this is shown in (3):

\[ T = T_1 T_2 T_3 \cdots T_{n-1} \]

Regarding to the dynamic model, it is described through the torque that the bird must perform in its joints.
in order to move the limbs. For an inverse dynamical model, as in the case of this work, this torque is obtained from the kinetic and potential energies, which according to the Lagrange-Euler model are given by the following expressions respectively (4 and 5).

\[
E_c = \frac{1}{2} I \dot{\theta}^2 
\]

\[
E_p = mgl \sin \theta
\]

where, \( I \) is the inertia moment and \( \theta \) is the angle from the link to the ground, \( m \) is the mass, \( g \) is gravity and \( l \) is elevation.

Then, the torque is given by (6)

\[
\tau_i = \frac{d}{dt} \left( \frac{\delta L}{\delta q_i} \right) - \frac{\delta L}{\delta q_i}, i = 1 \ldots n
\]

3. Methodology and Model Description

The proposed locomotion model is based on experimental data taken by means of a set of tests in a Columbia livia Dove and the previous results obtained\(^{25,26}\). Combining these results we expect to improve the parameter selection and the uniformity in the samples. Finally, through these parameters we define the matrix using the Craig nomenclature in order to describe our locomotion model in a mathematical form.

3.1 Biological Experiments

We measured morphologic parameters in 5 young Doves (Columbia livia) shooting them using a video camera with 14 mega pixels and 5x of optical zoom. Three of these Doves were captive while the other two were analyzed on the street. In this way, the four tests shown in Table 1, were taken in a young Dove in order to measure full-step length, step frequency, step velocity and mass. If we make a comparison between results, the third test shows more similitude with the results obtained\(^{25,26}\).

| Test | Step length (mm) | Step frequency (s-1) | Step velocity (mm/s) | Mass (g) |
|------|------------------|----------------------|---------------------|----------|
| 1    | 215              | 2.77                 | 596                 | 233      |
| 2    | 182              | 2.27                 | 414                 | 233      |
| 3    | 274              | 2.5                  | 685                 | 245      |
| 4    | 235              | 2.4                  | 655                 | 250      |

In Table 2, we show the bone and posterior limb dimensions for the same bird and two tests, which were obtained using a precision calibrator. Additionally, in Table 3 we show the mass for 4 Doves. The last test focuses on the Dove density measure and in this way the mass and inertial tensor for each bone, which are essential parameters for the kinetic energy calculation. To measure this density, first we had to calculate the bird’s volume submerging it in a recipient with a known area and filled with water. In this way, we obtained the 4 results shown in Table 4, which give us an average bird density of \( \frac{754.22 \text{ Kg}}{\text{m}^3} \).
Table 2. Bone and posterior limb dimensions

| Length                  | Test 1 | Test 2 |
|-------------------------|--------|--------|
| Femur (mm)              | 39.8   | 43.8   |
| Tibiotarsus (mm)        | 60.8   | 61.7   |
| Tarsometatarsus (mm)    | 32.2   | 32.9   |

Table 3. Dove mass for 4 individuals

| Bird  | Mass (g) |
|-------|----------|
| 1     | 250      |
| 2     | 270      |
| 3     | 310      |
| 4     | 368      |

Table 4. Bird density

|                  | Test 1 | Test 2 | Test 3 | Test 4 |
|------------------|--------|--------|--------|--------|
| Bird’s mass (kg) | 0.31   | 0.31   | 0.31   | 0.31   |
| Container area (m²) | 0.041616 | 0.041616 | 0.041616 | 0.041616 |
| Bird’s volume (m³) | 0.000332 | 0.000416 | 0.000522 | 0.000416 |
| Density (kg/m³)   | 931.1322 | 744.9058 | 595.9246 | 744.9058 |

3.2 Comparative Analysis

A comparison between our results and the results obtained is described in this section. First, in Table 5 we compare our experimental results about terrestrial locomotion, specifically those shown in the test 3 of Table 1, with results of Fujita, which were taken in 40 Doves and 113 steps, using video analysis and anatomic measures in dead Doves. Here we can observe that the results of our experiments demonstrate that the step length and velocity are greater than the values measured. Second, in Table 6 we compare our experimental results shown in Tables 2 and 3, and the results of about posterior limb bones dimensions. It is noticeable that there is not a considerable difference for the femur, tibiotarsus and tarsus-metatarsus dimensions between the three authors. However, the difference is considerable in terms of the mass, which is of 77.9 grams between results of Fujita and our results.

Table 5. Behavior parameters for terrestrial locomotion-comparative results

| Author          | Species | Step length | Step frequency | Step velocity |
|-----------------|---------|-------------|----------------|--------------|
| Masaki Fujita   | C. livia | 237.6 mm    | 2.593 s⁻¹      | 628.5 m/s    |
| Test 3 Table 1  | C. livia | 274 mm      | 2.5 s⁻¹        | 685 m/s      |

Finally, the step frequency, step velocity, mass and density are used to describe the inertial tensor, which defines the required energy to perform the movement. All this information is used to define the mathematical model of our approach, which is based in two modes, slow and moderate locomotion, as it is established in

4. Results

As we mentioned in the previous section, the locomotion model of this work has into account three concepts, the workspace, the kinematic model and the inertia tensor. Here we describe them along with the simulations results for each case.

4.1 Workspace

The workspace of a full step is determined through the maximum and minimum angles described by the joints during the locomotion process.

Table 6. Bone and posterior limb dimensions-comparative results

| Author/ source | Species | Femur length | Tibiotarsus length | Tarsometatarsus length | Mass   |
|----------------|---------|--------------|--------------------|------------------------|--------|
| Masaki Fujita  | C. livia | 45.1mm       | 59.1 mm            | 32.6 mm                | 347.9 g|
| Richard Johnston | C. livia | 39.1mm       | 58.1 mm            | 31.7 mm                | -      |
| Results Table 2 | C. livia | 39.8mm      | 60.8mm            | 32.2mm                | 270g   |
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Table 7. Compilation of the model parameters

| Parameters          | Values                                      | Test                |
|---------------------|---------------------------------------------|---------------------|
|                     | Slow walking                               | Moderate walking    |
| Step length         | 182 mm                                     | 237.6 mm            |
| Gait frequency      | 2.27 s⁻¹                                    | 2.59 s⁻¹            |
| Step velocity       | 414 mm/s                                    | 628.5 mm/s          |
| Mass                | 310 g                                       | 310 g               |
| Density             | 705.56 \( \frac{Kg}{m^3} \)                 | 705.56 \( \frac{Kg}{m^3} \) |
| Femur length        | 43.8 mm                                     | 43.8 mm             |
| Tibiotarsus length  | 61.7 mm                                     | 61.7 mm             |
| Tarsometatarsus length | 32.9 mm                                    | 32.9 mm             |
| Locomotion pattern  | Slow walking                                | Moderate walking    |

 respectively. For the slow locomotion case, the leg endpoint is located between the −55.6 mm and 102 mm over the movement line and 75 mm above the floor surface. For the moderate locomotion case, the leg endpoint is located between the −57 mm and 90 mm over the movement line and 76.7 mm above the floor surface.

Figure 6. Workspace in slow walking for a Dove (Columba livia).

4.2 Kinematic Analysis for the Bird Locomotion

Using the results shown in Table 7, we build the parameters matrix for each link. This matrix is described in Table 8. By means of the Craig procedure we define each reference point for each link as is depicted in Figure 8.

Figure 7. Workspace in moderate walking for a Dove (Columba livia).

Table 8. Parameters matrix - dennavit hartenberg

| Link | \( a_{(i-1)} \) (mm) | \( a_{(i-1)} \) (mm) | \( \theta_{(i)} \) (rad) |
|------|-----------------------|-----------------------|-------------------------|
| 1    | 0                     | 0                     | 0.7505                  |
| 2    | 0                     | 0                     | \( \theta_{(1)} \)     |
| 3    | 0                     | 43.8                  | \( \theta_{(3)} \)     |
| 4    | 0                     | 61.7                  | \( \theta_{(4)} \)     |
| 5    | 0                     | 32.9                  | 0                       |

The fixed reference point is located on the hip joint. The first reference point is oriented 43 degrees in relation
to the fixed point, and its translation is through the bird motion axis (x axis) depending on the type of step being analyzed. The proposed model is bi-dimensional and defined in the sagittal plane of the Dove, which means that the torsion angle (α) and the joint distances (d) are zero. The joint angles vary for each step sample as is established for slow and moderate locomotion.

Now, having the reference points and the necessary parameters for the matrix (Table 8), we obtain the following homogeneous transformation matrix

\[
\begin{bmatrix}
\cos(\theta_1 + \theta_2 + \theta_3 + \theta_4) & -\sin(\theta_1 + \theta_2 + \theta_3 + \theta_4) & 0 & 0 \\
\sin(\theta_1 + \theta_2 + \theta_3 + \theta_4) & \cos(\theta_1 + \theta_2 + \theta_3 + \theta_4) & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

With this matrix and the time variation for the joint angles, it is possible to describe the slow and moderate locomotions for a step, as we can see in Figures 9 and 10. The movement including both Dove feet is shown in Figures 11 and 12 for slow and moderate locomotion, respectively.

4.3 Energetic Analysis

In this section, we use the parameters shown in Table 9 in order to calculate kinematic energy, potential energy and the variation of the total energy.
According to (4), the kinetic energy calculation requires the angular and lineal velocities for each step sample. These are calculated using respectively the expressions

$$\dot{w}_{i+1}^i = \dot{r}_i^i R_{i+1}^i + \dot{\theta}_{i+1}^i Z_{i+1}^i$$  

(7)

and

$$\dot{v}_{i+1}^i = \dot{r}_i^i R_{i+1}^i \left( v_i^i + w_i^i x P_{i+1}^i \right)$$  

(8),

where, \(i=\{1,\ldots,5\}\) represents the joint variables, \(R\) is the rotation matrix and \(P\) the mass center position for each bone. Additionally, the calculation of this energy requires the inertial tensor shown in the fifth column of Table 9. On the other hand, the potential energy calculation requires the bird mass, the gravitational constant and the height of each link in relation to the ground, which in this case is given by the third column of Table 9. Once the energies are obtained, we use the Lagrange-Euler equation given in (6) to develop a Matlab algorithm in order to describe through simulations the energy consumption of the system. The results are shown in Figures 13 and 14 to contrast the kinetic energy and the system energy consumption on each link (femur, tibia-tarsus and tarsus-metatarsus) and the hip both for slow and moderate locomotions, respectively. The feet kinematic energy is calculated having into account each step sample on the full step, which results in 89mJ for slow locomotion and 129.5mJ for moderate locomotion. Taking the duration time for slow and moderate locomotions, we calculate the power for each case differentiating the energy over these periods of time. In this sense, the power for slow locomotion is 232mW and for moderate locomotion is 295mW.

### 4.4 Efficiency Analysis

The efficiency analysis is performed through a comparison between the results shown in (27) and the results of

| Link          | Mass (g) | Length (mm) | Mass center (mm) | Inertia tensor (gr x cm²) |
|---------------|---------|-------------|------------------|--------------------------|
| Trunk         | 295.5   | 98.3        | 43.8             | $\begin{bmatrix} 2.73e3 & 0 & 0 \\ 0 & 2.64e3 & 0 \\ 0 & 0 & 2.64e3 \end{bmatrix}$ |
| Femur         | 8.94    | 43.8        | 18.42            | $\begin{bmatrix} 4.76 & 0 & 0 \\ 0 & 16.86 & 0 \\ 0 & 0 & 16.86 \end{bmatrix}$ |
| Tibiotarsus   | 4.35    | 61.7        | 25.25            | $\begin{bmatrix} 0.83 & 0 & 0 \\ 0 & 15.30 & 0 \\ 0 & 0 & 15.30 \end{bmatrix}$ |
| Tarsometatarsus| 0.29    | 32.9        | 15.24            | $\begin{bmatrix} 6.15e^{-3} & 0 & 0 \\ 0 & 31.24e^{-2} & 0 \\ 0 & 0 & 31.24e^{-2} \end{bmatrix}$ |
In our approach, $E_{\text{metab}}$ we calculate for slow and moderate locomotion using the cost coefficient 0.225 J, which corresponds to Quails, a bird with similar characteristics to the *Columba livia*. For slow locomotion we have from Table 7 that $t_c$ is equal to the 65% of the full step, i.e., 0.287 s. Then, the limb power during a step is 2.34 W. For moderate locomotion, is the 60% of the full step, i.e., 0.231 s. This means that the limb power during a step is 2.92 W. In this sense, a comparison between our results and results shown in Roberts reflect an efficiency of 9.9% and 10.10% for slow and moderate locomotion, respectively.

5. Conclusions

In this work we propose a kinematic model inspired in the dove *Columba livia*. This model expects to expand the knowledge about the bio-mechanical patterns in birds that can be implemented in biped robots in order to address the drawbacks of locomotion over irregular terrains where wheel-locomotive solutions are inadequate. The selected dove offers a general locomotive pattern and allows us to make comparative analysis since it is a common bird in the environment where this study was performed.

The mathematical description used in this approach uses the matrices and the Craig nomenclature. The results and comparative analysis demonstrate that these mathematical tools produce good and consistent results and low complexity when they are computationally implemented. However, a more exact model could be developed if successive screw analysis is included in order to obtain results closer to reality.

We compare the results of this model and the other obtaining efficiency values of 9.9% and 10.10% for slow and moderate locomotion. These efficiency values could be improved if head and torso analysis are included in this model.

6. References

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