The RoboCoq Project: Modelling and Design of Bird-like Robot

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ABSTRACT

The RoboCoq project aims at designing a prototype of autonomous biped based on the avian model. According to biological studies conducted at National Museum of Natural History in Paris (MNHN) the locomotion system of birds appears to be more efficient than the human model in terms of stability, stride length and mobility. Moreover due to its morphology the foot of a bird seems to be more polyvalent and suitable for support and crossing of pebbly terrain. The objective of this project is to design a robot capable of exploring cluttered environments. The design of the robot will rely on experimental kinematics and dynamic data obtained from the animal. The information collected will serve as a basis for modelling and simulating the locomotion system of the bird, and will help reproduce the head-bobbing reflex on the robot.

This project has just started and involves the participation of biologists and roboticians issued from the MNHN, the LNRS, and the LRV. This paper presents some features of the avian model compared with the human model, describes the experimental protocol to be conducted to get all the biological data from the animal, gives a first simplified kinematics model of the locomotion system presents as well as a direct geometric model. The model constructed under ADAMS is exposed at the end of the article.
1. INTRODUCTION

Biped robots encounter a lot of interest in several countries. Oddly they are all inspired by the human model except some prototypes built in the MIT and others built to imitate the locomotion system of biped dinosaurs. In Japan, researchers and industrial firm engineers are working on building complete prototypes capable of walking and seeing like Man. A robot that looks like and acts like a human should appear more friendly to the people around who may interact with it and trust it.

In France researchers from INRIA designed and built a human biped robot called BIP to study problems related to walking gait generation and control [1]. The machine was designed to move indoors autonomously, walk on slightly inclined surfaces, and climb up human-scale stairs.

In the United States scientists from MIT [2] have focused on proving the importance of using compliance in a walking system. Active joints like electric servos are responsible for a certain inertia and friction that impose the dynamics of the robot. The impedance of such actuators is very high with respect to the leg structure. Passive mechanisms allow for reducing joint impedance and approximating torque source at the joints. The use of passive mechanisms at foot level provides better interaction with the ground by using less rigid trajectories than those produced by means of electric actuators. MIT researchers have favoured the natural dynamics of members issued by muscles rather than the dynamics of actuators. For this purpose they designed series elastic actuators [2], where a spring is placed in series with the output of the actuator, after the gear reduction. These mechanisms feature low impedance and reduced friction. Among the biped robots they designed the Spring Flamingo robot looks like a bird [2]. It is a planar robot with three rotary joints per leg, one at the hip, one at the knee and the last at the ankle. Joints are actuated through cables. Motors are located on the upper part of the robot. The robot’s leg structure features only 3 degrees of freedom (d.o.f.) whereas the leg of a bird has 6 d.o.f.. However the objective of the research in MIT was to demonstrate the benefit of using such compliant mechanisms in biped robots, and to develop adapted walking algorithms.

In the project described in this paper, the RoboCoq robot must be capable of operating in 3D space, and not constrained to move in 2D space. Moreover it should be autonomous in terms of power and be able to choose the right gait to use by itself to cross the irregularities it may encounter along its path. If possible, RoboCoq should be able to cross human-scale environments. Compared to the BIP robot, RoboCoq will be inspired by the avian model, which should confer it better performances. Studies conducted in MIT are very useful and give some hints for designing a compliant bird-like leg structure.

2. THE AVIAN MODEL

Due to the anatomical requirements for the flight, birds represent the most homogenous class among the vertebrates from a morphological point of view. At the same time, birds present an extensive adaptive radiation and live in every kind of environment: aquatic, terrestrial, arboreal … [3][4][5].

Birds use two locomotive apparatuses. The first one comprises the wing and the tail, and is used mainly for the flight. The second one comprises the legs, used mainly for terrestrial locomotion. It is not the purpose of this project to design a complete bird-like robot but to focus on the leg structure. The animal chosen to conduct biological studies is
the quail. The quails used have been selected for their adaptability [6][7]. They are well suited for walking.

Birds are the only animals to share a strict bipedality with humans. Several characteristics suggest that the avian model is more stable than the human model [8]. As a matter of fact the centre of gravity is located under the hip joint (fig. 1) whereas among humans it is located above in the lower part of the trunk. Among birds the trunk is suspended by the hip joints.

![Rooster skeleton showing leg joints](image)

Fig.1. Rooster skeleton showing leg joints (Modified from [9])

The hind limb of the birds is characterized by the presence of three segments (fig. 1). The first one that joins the hip and the knee joints is nearly horizontal and allows for bringing back the leg below the gravity centre. It may also play the role of a stabilizer of the trunk. The two other segments are the most mobile parts.

The "foot" of the birds is primitively formed by four fingers only, with three toes pointing forward and one pointing backward. It is therefore much simpler than the human foot. The flexibility of the 4 fingers and the large base they form allow high stability, even on irregular ground.

If we compare the stride length with respect to the leg height in the table below, we have a ratio of 1 for the human model compared to a ratio up to 2.2 for the quail.

<table>
<thead>
<tr>
<th>features</th>
<th>Human</th>
<th>Bird (quail)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stride length</td>
<td>100 cm</td>
<td>20 cm</td>
</tr>
<tr>
<td>Hip height</td>
<td>100 cm</td>
<td>9 cm</td>
</tr>
<tr>
<td>Ratio (stride length over hip height)</td>
<td>1</td>
<td>2.2</td>
</tr>
</tbody>
</table>
The bird model appears to be better than the human one in terms of stability and stride length. Another difference with the human model lies in the leg structure, the human model leg segments are located in the same plane at rest, whereas in the bird one the leg segments feature a specific 3D orientation with each other.

3. DESIGNING THE BIRD LOCOMOTION SYSTEM MODEL

3.1 Biological data acquisition

The first phase of the project will consist of analysing the dynamic and kinematics features of walking quails. The force exchanged between the bird and the ground as well as the movements of the centre of mass during locomotion will be studied using force plates. Figure 2 shows the three piezoelectric sensors that will be used to design the experimental force plate. These piezoelectric sensors are manufactured by KISTLER. The kinematics data, especially the displacement of skeletal segments, will be collected by X-ray analysis coupled with high rate digital camera acquisition. This study will allow us to measure the amplitude and the phase shift in movements of each leg, to determine the mechanisms responsible for the animal balance, and to define the strategy adopted by birds when walking on an irregular ground. It will also give us information for dimensioning the segments and actuators for the prototype.

In a second phase we will choose the kinematics and mechanical characteristics of the powered segments of the robot. Then we will test them by simulation. The various loads and physical parameters related to the mechanics of the segments will be used to calculate the dimensioning of the joints, actuators, masses and inertia. The geometrical placement (position and orientation) of the various elements such as segments, joints, actuators and proprio- and exteroceptive sensors will be adapted to the robotic structure, which will be different from the bird structure. (In this paper only the first part is concerned).

3.2 Simplified kinematics structure

Considering the leg model of a bird, one can see that it owns one additional segment with respect to the human model. In fact, both models feature a hip joint and a knee joint. Whereas in the human model the heel belongs to the foot, in the avian model a “heel joint” is linked to the foot by a third segment. This feature should confer a better mobility to a robot based on the avian model.
First biological observations permit to define a simplified kinematics model that is depicted in figure 3.

The model has 6 degrees of freedom for each leg, including 2 active rotations at the hip level, 1 active rotation at the knee level, 1 active rotation at the heel and 2 active rotations at the foot joint. The rotation axes of the knee and the heel, as well as one rotation axis of the hip and of the foot articulations will be parallel in the frontal plane. The second articulation of the foot will have its axis parallel with the direction of displacement. The second articulation of the hip will allow rotation around the vertical axis.

In contrast with the human model or the BIP robot, the movements of the trunk cannot be decoupled with respect to the legs. In fact when the bird walks its body follows an almost straight horizontal line. This is different for the human model where the centre of gravity oscillates periodically along the vertical.

The study of the avian foot and its robotic reproduction appears to be difficult. Even if it seems less complex than the human foot, the role of the toes in the walking balance keeping is determining. It is necessary to use elastic passive mechanisms and tactile sensors to imitate the toe holding and leaving ground. Moreover a special blocking device of the toes should be incorporated in order (for the robot) to stand firm on the foot when thrusting the body.

Therefore the locomotion system of RoboCoq should be equipped with 12 active rotary joints, and with 3 or 4 passive mechanisms for each foot.

![Fig.3. RoboCoq simplified kinematics scheme](image)

### 3.3 Deriving a direct geometric model

Considering that bird’s foot is relatively complex to be modelled, the idea was to divide the problem into progressive steps. At first, we started by getting the geometric model of a single leg and then attempting to reproduce the trajectories of the different existing angles obtained by the biologists colleagues of the Museum. The direct geometric model is a mathematical model that allows expressing the location of the terminal organ in function of the articulation variables. This model is important for the design of control laws [10][11][12].

As listed before, the bird studied possesses 6 degrees of freedom per leg. The proposed diagram (Fig.4) represents the arrangement and the orientations of the different pivot joints:
Fig. 4. Geometric model of a bird leg

By analysing Figure 4, we can notice that at the hip level, we have two pivots. The first one is around the Z axis and the second one around the Y axis. We consider that the vertical rotation axis should be fixed with respect to the body, hence the first hip joint attached to the body is the rotary joint whose axis is vertical (see figure 4).

At the knee and the heel level, we have rotations around the y axis. At this time, we don’t have yet the information whether these rotations are coplanar or not. For the while, we suppose that they are. Fixed angle rotation matrices may be introduced to take into account this constraint. At the foot level, the joint is modelled by two pivots, around Y and X axis respectively. This order has been chosen to help the control of stability of the body. The distances between the pivots have been modelled as constant 3 dimension translations. Since we have 6 articulations, we will have six homogeneous transformation matrices (frame transformation).

The homogeneous matrix describing a rotation is given by:

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) \\ 0 & \sin(\theta) & \cos(\theta) \end{bmatrix}$$

For a rotation around the X axis.

$$R_y(\theta) = \begin{bmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) \end{bmatrix}$$

For a rotation around the Y axis.
\[ R_z(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \] For a rotation around the Z axis.

\( \theta \) being the angle between the two segments linked by the articulation.

The distance between the articulations is expressed by vector:

\[ D = \begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix} \]

\( d_x, d_y \) and \( d_z \) being the distances along the X, Y and Z axis respectively between the origins of the frames.

The combination of the two articulations yields a transition matrix of the form:

\[ T = \begin{bmatrix} R_{(x,y,z)} & D \\ 0 & 0 & 0 & 1 \end{bmatrix} \]

\( (\text{For a rotation round the X axis}) \)

\[ T = \begin{bmatrix} 1 & 0 & 0 & d_x \\ 0 & \cos(\theta) & -\sin(\theta) & d_y \\ 0 & \sin(\theta) & \cos(\theta) & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \]

The product of the transitions matrices starting from the last one will give the transition matrix from the first frame to the last one. By using formal computations tools, and by following the previous steps, we can obtain the global transition matrix:

\[ 6T_0 = 1T_i 2T_j 3T_2 4T_3 5T_4 6T_5 \]

\( 6T_0 \) Being the transition matrix from the 1\(^{\text{st}}\) frame to the j\(^{\text{th}}\) one.

**4. SIMULATION MODEL:**

We use ADAMS (Mechanical dynamics) to run simulations. The software allows building models and applying control laws to generate desired behaviours. A 3D model representing the quail was constructed. The foot has not be taken into account yet. The following figures represent the dorsal, front and the side views.

Fig.5. ADAMS model
The constructed model takes into account the data of the quail at rest provided by the colleagues of the Museum.

This model is to be improved progressively by comparing the simulation results with the measurements collected in the Museum: kinematics data and the efforts measured by the force platform.

CONCLUSION

This paper has presented a simplified kinematics model build from the data collected in the Museum. A direct geometric model of a single leg has been derived as a first step. The 3 dimensions model constructed under ADAMS is exposed. Intensive simulations must be done to improve the proposed model. New data from the Museum will permit to generate appropriate trajectories and to ensure the coordination between the two legs. Also as a perspective, a dynamic model should be derived to design non linear controllers.

REFERENCES: