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# Finding adequate optimization criteria to solve inverse kinematics of redundant bird leg mechanism

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## Abstract

In this paper we shall present the progress of the ROBOCOQ project. This project aims to design a prototype of autonomous biped based on the avian model, capable of exploring cluttered environments. This design relies on experimental kinematics data obtained from the quail. The experimental protocol used to reconstruct a 3D model is presented in this paper as well as the procedure and criteria employed to find an optimal inverse kinematics control.

**Keywords:** Kinematics, inverse geometric model, bird-like biped walk, trajectories, optimal posture.

## 1 Introduction

Birds and humans are the only two bipeds that colonized the planet. Birds can be found everywhere on the Earth in every kind of environment. Biologists of the MNHN believe that the locomotion system of birds presents interesting features and is more efficient than the human one in terms of stability, stride length and mobility [1][2][3]. A biped robot presents several advantages in comparison with other kinds of legged locomotion. Having only two legs allows a large polyvalence in terms of clearing obstacles such as stairs and cluttered environments. The concept of designing biped robots encounters a large interest among researchers those last decades. However many projects consider the human model for the robot structure design. Some scientists have tried to explore other types of biped configuration to investigate whether they can be more efficient than the

human one. In that spirit the ROBOCOQ project [4] has started and aims to check the efficiency of the bird structure.

In this paper we describe the procedure followed to gather the necessary data, and the tools to make a kinematics analysis. The measurements carried out in the museum with real walking quails are exploited to reconstruct a 3D movement. A geometric model for the bird leg is proposed and calibrated using these measurements. Each leg of the bird features one degree of redundancy. Trajectories issued from the reconstructed 3D data are used to test some optimization criteria that are needed for solving the inverse kinematics model. In this paper we shall present some results of this analysis and give future work prospects.

## 2 Kinematics and Biological analysis

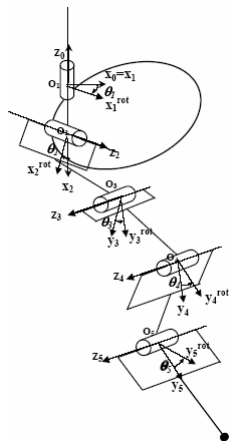
We conducted several experiments on the birds to understand the way they walk and they react in different environments and their morphology [5][6][7]. We noticed that the quail can adopt different postures depending on the nature of the ground and the environment. When filmed from the lateral side for example, the quail had a relative high-legged posture whereas when being filmed from the top, the posture was slightly low-legged. It was as if the animal was trying to protect itself from the bulky device placed above the walkway to capture video. For kinematics data acquisition small lead bullets were attached to the wanted points in the quail body to observe the motion trajectory of the different segments and joints of the bird during walk. Quails had to move on a walkway. An X-ray device coupled with a video-camera was used to collect the coordinates of the joints. These experiments provided us with two non simultaneous views, a lateral one and a dorsal one.

To overcome this drawback, we set up an experimental protocol to synchronize the two views and reconstruct the 3D cycle. The first step of the work is to filter the collected data. The second step consists of scaling the data so that the number of samples is the same for both signals. The signals must then be interpolated using FFT to get continuous signals or discrete values at the same sampling times [8] [9]. This procedure is described in a previous paper [10]. Once the two views are synchronized, we can easily reconstruct 3D data series of a walking cycle [10].

### 3 Data exploitation

#### 3.1 Kinematics model

To study the bird locomotion we have focused on the structure of the leg and tried to get a faithful kinematics model. The scheme proposed in **fig.1.** shows the direct geometric model used. It is decomposed into 5 rotations named respectively  $(\theta_1, \theta_2, \theta_3, \theta_4, \theta_5)$  starting from the hip. Three are located at the hip, one at the knee and one at the ankle. The three segments of the leg are contained in the same plane, that we call the leg plane. By convention, whatever the direction of motion we set the data so that the animal is walking from the left to the right. We also consider the right leg [11].



**Fig.1.** Kinematics scheme and convention of reference frames.

Axis x is along the direction of motion. Axis z is the vertical axis. Axis y is oriented toward the body.

The 3D direct geometric model expresses the 3D coordinates of the foot within the body reference frame as a function of the joint angles.

#### 3.2 Evaluations of the joint angles during a walking cycle

Since our objective is to inverse the kinematics, it is useful to calculate the joint angles related to the kinematics model from the 3D biological data. As a matter of fact, we can get the model joint angle as a function of time

and have an estimation of the range and the minimal and the maximum angles for each joint. These values can then be used as non linear constraints for the optimization issue (see § 4). We design a graphical animation interface based on OpenGL™ that enables to play the leg motion cycle and to zoom at it from different viewpoints. Before refreshing the next view, the program calculates all the model joints from the 3D coordinates of the biological joints. The algorithm used can be divided into two main parts. The first one concerns the knee and the ankle joints. The second part deals with the joint angles at the hip. There are n frames beginning with frame 1 taken at time  $t_0$ , frame k taken at time  $t_{k-1}$ , etc. The biological leg joints in frame k are designated by  $H_k$ ,  $K_k$ ,  $A_k$ , and  $F_k$ .

The 3D joints coordinates in frame k are stored respectively in:  $\{(x_H^k, y_H^k, z_H^k), (x_K^k, y_K^k, z_K^k), (x_A^k, y_A^k, z_A^k), (x_F^k, y_F^k, z_F^k)\}$  starting from the hip. The rotation axes are noted  $z_i$ , where i designates the number of the rotation, starting from the hip. Five pairs of reference frames  $(R_i, R_i^{rot})$  have been defined, for  $i \in \{1, 2, 3, 4, 5\}$  such that we have:

$$R_i(x_i; y_i; z_i) \xrightarrow{rot(\theta_i)} R_i^{rot} \quad (1)$$

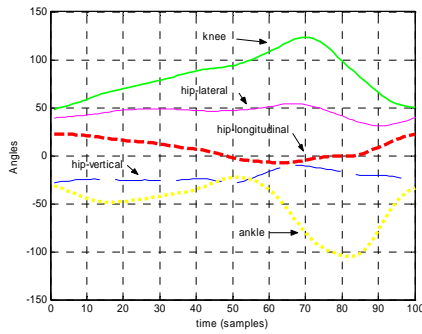
An initial reference frame linked to the body is also defined as  $R_0$  having as base:  $\{x_0; y_0; z_0\}$  where  $x_0$  and  $y_0$  define the horizontal plane, and  $z_0$  the vertical axis. The expression to find the joint angles of the knee and the ankle can be obtained by using the cross product and the scalar product of the normal to the first two segments,  $H^k K^k$  and  $K^k A^k$ , and the normal to the last two segments,  $K^k A^k$  and  $A^k F^k$ . The normal to the leg plane is the average of these two normals. For the hip we start by calculating  $\theta_2^k$ . The trick is to express  $z_3^k$  inside the reference frame in two different ways. First we express  $z_3^k$  in  $R_3$  and apply a rotation of  $(-\theta_2^k)$ . Second we have  $z_3^k$  expressed in  $R_0$  because  $z_3^k$  is the normal to the leg plane, the normal being calculated by the average of two cross-products of both pairs of leg segments. We apply a rotation of  $\theta_1^k$  to  $z_3^k(R_0)$  in order to be in the same reference frame for both equations. Manipulating these two equations leads to a sine/cosine equation of the following form:

$$A.\cos(\theta_2^k) + B.\sin(\theta_2^k) = C \quad (2)$$

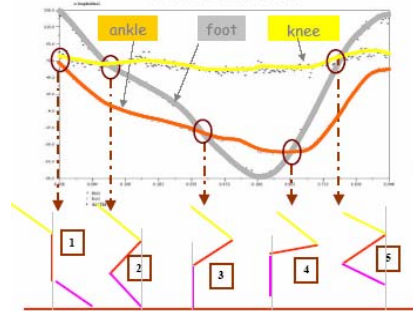
Where  $A$ ,  $B$  and  $C$  are scalars.  $\theta_1^k$  doesn't appear here because we focus on the component of the vector  $z_3^k$  projected on  $z_1$ .

Solving this equation gives two solutions where one of them is physically impossible to reach. To find the remaining two joints angles of the hip namely  $\theta_1^k$  and  $\theta_3^k$ , a similar procedure must be adopted for both of them. From one of the previous equations used to find  $\theta_2^k$ , it is possible to get  $\theta_1^k$  and  $\theta_3^k$ . The procedure consists of calculating the angle of rotation, knowing its axis, an initial and a final vector.

If we had a large panel of 3D coordinates data issued from measurements, it would be possible to calculate calibration tables of joint angles that can be used to control the motion of the leg. However it is better to design an algorithm capable of calculating the joint angles only from the foot 3D coordinates by solving the inverse kinematics.



**Fig. 2.** Calculated joint angles variations



**Fig. 3.** x-coordinates of knee, ankle and foot as a function of time

**Fig.2.** presents the model joint angles variation during a walking cycle resulting from the developed algorithm and using a given 3D reconstructed data.

#### 4 Solving the inverse kinematics model

This part deals with the procedure adopted to solve the inverse kinematics model problem. Indeed the leg of the bird features one degree of redundancy. For a given position of the foot we can have many possible postures. In the previous part we have used the 3D data to have an idea of the joint angles variations. We use this result to limit the reachable area of

each joint. The program is developed under MATLAB R13 using some functions of the optimization tool-box. The inputs of the algorithms are:

- The 3D coordinates of the wanted foot position,
- Up and down limit angles of each joint,
- The expression of the direct geometric model,
- An initial position for each joint angle,
- An optimization criterion to be followed to reach the convergence.

The outputs are the computed joint angles that can be sent to the actuators that drive the motion.

In this program we exploit five specific configurations of the leg that are extracted from the longitudinal axis coordinates of all biological joint as a function of time. These configurations are: touchdown; middle of the propulsion; beginning of lift-off; end of lift-off; beginning of touchdown (see **fig.3.**). The program allows to perform two operations. The first consists of computing the joint angles of a given single position. It detects the nearest posture stated above and minimizes the following quadratic criterion.

$$C = \sum_{i=1}^5 (\theta_i^k - \alpha_i^j)^2 \quad (3)$$

Where  $i$  is the joint number,  $j$  is the number of the nearest configuration stated above (**Fig.3.**) and  $k$  is the number of the current iteration.  $\alpha_i$  is the angle related to joint  $i$  and configuration  $j$ .

The second possibility is to input a trajectory of the foot as a vector. The program performs an optimization between 2 successive positions starting from the nearest posture. The optimization algorithm aims at minimizing the following quadratic criterion:

$$C = \sum_{i=1}^5 (\theta_i^k - \theta_i^{k-1})^2 \quad (4)$$

This procedure yields a smooth movement and avoids having a sharp variation of the posture.

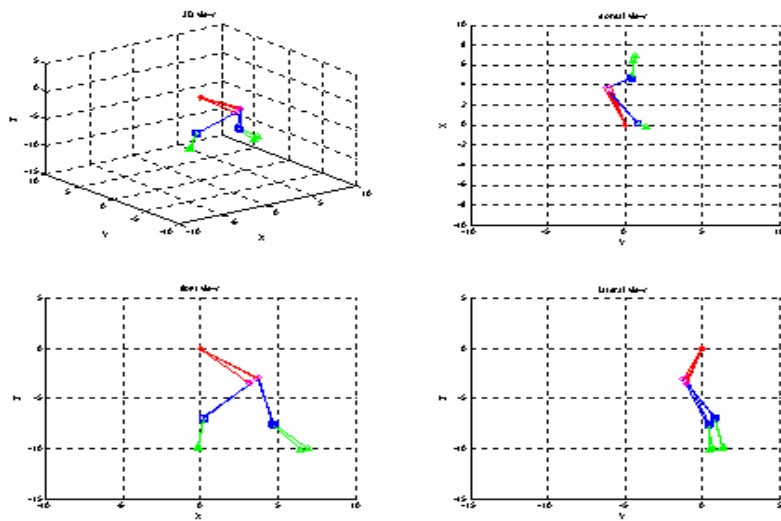
## 5 Simulations and results

**Fig.4.** presents the results of the simulation that takes two known positions of the foot as inputs. The scheme compares the results with the joint angle trajectories issued from the calculated model (see section 3.2). We note that the hip is fixed because it has been chosen as a reference. We can no-

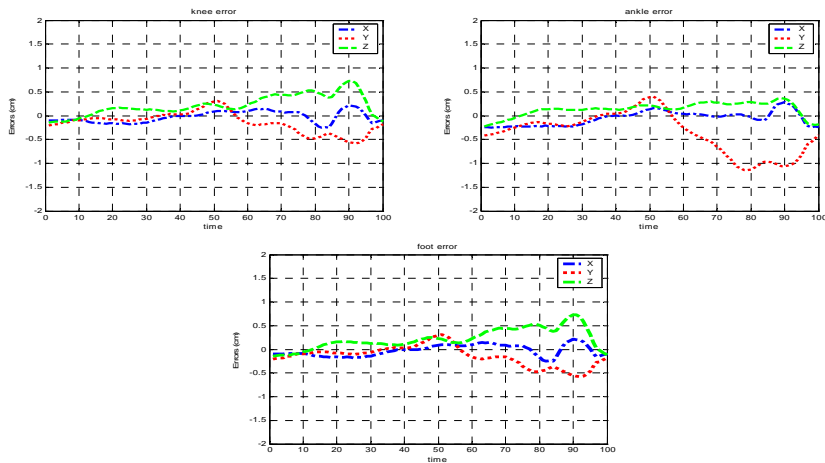


tice that for each case the calculated postures fit almost the original ones. We have less than 10% errors for the worst cases of the simulated points. These errors may be due to some numerical approximations.

We tried to recover a full trajectory using the developed algorithms. As input we use a measured trajectory of the foot during the walking cycle. **Fig.5.** shows the positions errors for the coordinates of each computed joint. We can notice that even for trajectories the errors are bounded and never exceed 10% of the total length of the segments.



**Fig.4.** Comparative of the calculated position and the measured ones



**Fig.5.** The position errors of each articulation

## Conclusion:

This paper describes the procedure and the tools used to perform a kinematics analysis of a bird leg motion. A solution is proposed to overcome the redundancy of this structure and to get the inverse geometric model.

The perspective of this work is to define a kinematics control in order to reproduce the 3D leg movement which will be decomposed into two parts:

- The movement of the leg plane which will be controlled by the normal to the plane.
- The movement of the leg segments inside the plane.

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