Motion and Force measures on tortoises to design and control a biomimetic quadruped robot

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Abstract This paper is concerned with locomotion systems modelling and control; in particular the locomotion of bio-mimetically inspired quadruped robots. Using observations and experimentations, we propose a virtual model of quadruped with no dorsal vertebrae, such as the case in the majority of legged mobile robots. This condition applies to the terrestrial tortoise and makes it a good example for bio-mimetic inspiration. Extensive experiments *in vivo* and *in vitro* are conducted to estimate the motion, the kinematics and the dynamic properties of two living subjects and a dead one. The experimental results are used to model, control and simulate the motion of a tortoise-like quadruped robot. The result is TATOR II, a successful example of robots mimicking the mechanical design and motion trajectories of animals; it is a linkage of 15 rigid bodies articulated by 22 degrees of freedom, it is built on the ADAMS-View platform and is shown to perform through animation with a motion controller. Analyses of the influence of the phase between legs on the robot speed are also presented. Conclusions and future Works are detailed.

1 Introduction

This study is achieved in the Institute of Intelligent Systems and Robotics (ISIR) with partnership with the UMR 7179 of the National Museum of Natural History in Paris. We expect that by studying the locomotion of living animals, we can find interesting parameters that could be used in mobile robotics and are invariant from specie to another. We also expect to create a model that helps to study the locomotion of current and extinct species. Two animals are studied: the European hedgehog (J.Villanova, 2003), and the Hermann tortoise (B.Hennion, 2006). Two virtual models are built; a bi-dimensional model of the hedgehog and a 3D model of the Herman Tortoise called TATOR I. In this study, we will present a new and much precise methods for creating a bio-mimetic virtual quadruped robot inspired from terrestrial tortoises. This model is called TATOR II. The remaining of this paper is organized as follows: In section II we describe the experiments *in vivo* and *in vitro* performed on animals; in section III, we present the dynamic model TATOR II. Section IV highlights the contributions and the future perspectives. Figure 1 presents a basic summary of the study.

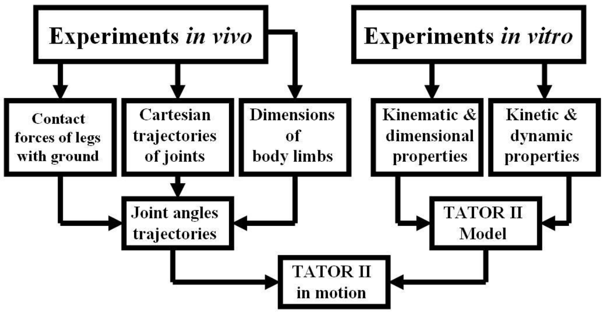

Figure 1. Basic summary of the study

2 Experiments on animals

We perform experiments on three adult tortoises. Two are alive (subject I and subject II) and the third (subject III) is dead for natural reasons (this subject has approximately the same inertial and dimensional properties of subject I). These experiments are divided into two categories: *in vivo* and *in vitro*. We use measures on subject III to create the virtual model TATOR II, while we use those on subject I to control it. We choose two different subjects to model and control TATOR II, because the dissection is forbidden on living subjects.

2.1 Experiments *in Vivo*

The experimental bench (Figure 2) used during these experiments is composed of: a video camera filming at 25 frames per second, an X-ray generator, a brightness amplifier, a digital camera filming at 50 frames per second and four piezoelectric force sensors mounted under four beams of wood. All measures are synchronized and nine metallic markers are attached

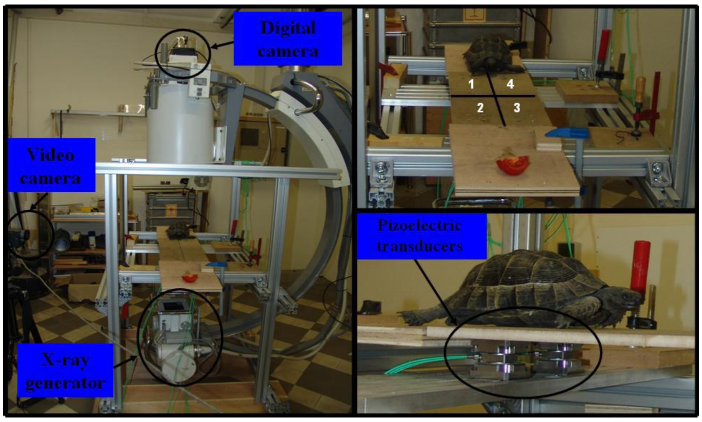

Figure 2. Experimental setup used to record the motion of studied subject in the dorsal and frontal plane and the contact forces of legs with the ground.

to subject I shell; these markers are used to measure the shell motion. Subject I in motion is filmed in the dorsal plane using cineradiography (Figure 3) and in the lateral plane using a video camera.

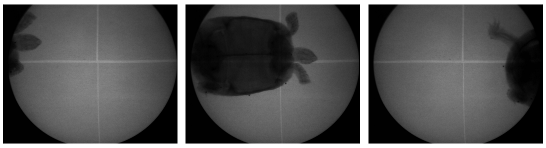

Figure 3. X-Rays video shoot of subject I in motion Top view

The used sensors measure only the three components of the contact force vector; we consider that the contacts are punctual. For economical reasons, we activate sensors 1, 2 and 3 (see Figure 2). Many trials are performed on subject I; in this paper we analyse the recording of sensor 3 for a given trial. However the logic is the same for sensor 1 and 2 outputs. The Figure 4 shows the recordings of sensor 3, three quantities are measured: the three components of the ground-reaction force on subject I right fore-limb, the sum of the three components of the ground-reaction force on subject I right limbs and the three coordinates of the ground reaction-force on subject I right hind-limb. From recording of sensor 3, we measure the ground-reaction forces on the right hind and fore limbs for more then a

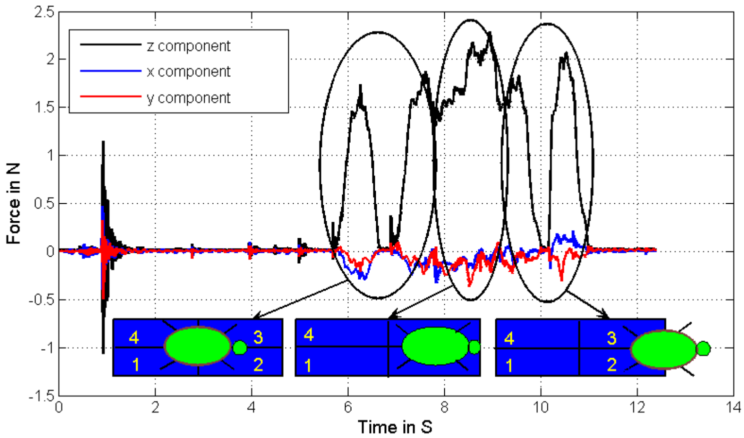

Figure 4. Recording of sensor 3 from a trial on subject I in motion.

locomotion cycle. We repeat the same analysis for the outputs of sensors 1 and 2. From these recordings we have measures of the ground-reaction forces on the left limbs for more then a locomotion cycle. In spite the use of three among four existing sensors, we have measures of the ground-reaction forces on each limb. The recording on subject I in motion shows that it uses its hind limbs to accelerate and the fore limbs to decelerate. This result is also observed when analysing ground-reaction forces on subject II limbs. An Important experimental result that should be investigated by performing experiments on more living specimens. Nevertheless, the x-ray films show that the shell-femur and the shell-scapula articulations are difficult to identify. An original method to solve this problem and to measure the length of internal limbs is detailed in ((DAOU, 2009)). The acquisition of the Cartesian coordinates of special points is done using a home made software developed using MATLAB.

2.2 Experiments *in Vitro*

These experiments are conducted on subject III to measure its inertial properties and to model its kinematics. We digitalize the shell, the markers, and the femur-shell and scapula-shell joints using a *Microscribe*. We dissect the tortoise and measure the weight of body limbs. We reconstruct the shell using Solidworks and we record its inertial properties. Due to the complex geometry and the small weight of other limbs, we can not apply this approach to calculate the inertial properties of all limbs; the limbs are modelled using cylinders having the same weight and length (J.Villanova, 2003). The bones are digitalized using a special medical scanner. The kinematics of the tortoise is approximated by two kinds of joints: spherical and revolute (Figure 5). We use a mechanical method adapted to biology to define the axe of rotation of revolute joint between the bones i and i+1 (DAOU, 2009).

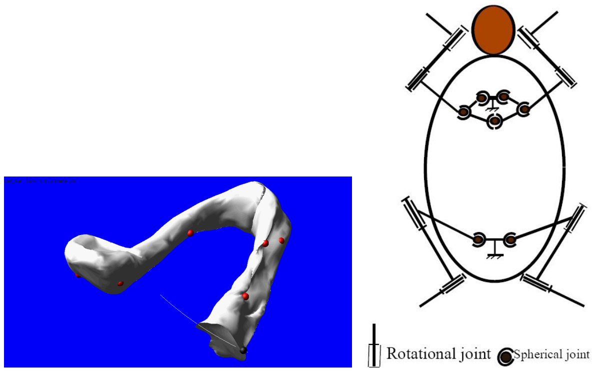

Figure 5. Reconstruted bones an markers; Functional diagram of the tortoise kinematics.

3 TATOR II Model

We use the collected data from the *in vitro* experiments to create a three-dimensional model of the tortoise. It is called TATOR II and built using the MSC ADAMS commercial software. It is a linkage of 15 rigid bodies articulated by 22 degree-of freedom; it imitates the mechanical design of subject III and it is controlled from experiments on subject I in motion. The model consists of the shell imported from Solidworks articulated to four legs. The friction and contact properties of the unilateral joint formed between the foot and the ground are modelled using the impact and coulomb friction modelling options in ADAMS. An experimental method is used to measure the static and dynamic coefficient of friction (B.Hennion and J-C.Guinot, 2005). Due to imprecision in Cartesian trajectories measures, a classical method to solve the inverse geometry problem is not possible. To solve this problem, we create two models of the left limbs using ADAMS platform (Figure 6). In both models the shell is created using the attached markers on subject I during the experiments *in vivo*.

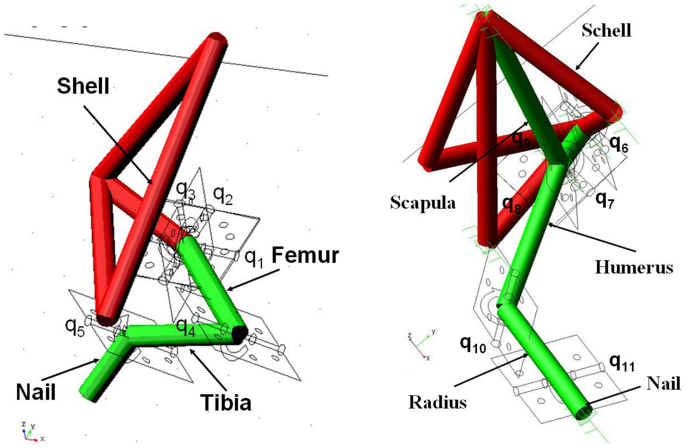

Figure 6. Models of the left limbs used to solve the inverse geometry problem;hind and fore limb.

We animate the markers, the intermediate bodies (black spheres in Figure 7) and the claw contact point with the ground using the Cartesian trajectories of particular anatomical points for a stance to stride movement of each limb measured during the experiments *in vivo*. We choose to use

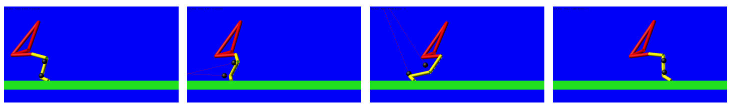

Figure 7. Model of the left hind limb animated by the measured trajectories.

intermediate bodies because we can not track all measured Cartesians trajectories due to imprecision in measures. We record the joint angles and we interpolate it using Fourier series. We observe that two joint angles coordinate of the shell-scapula spherical joint articulation are related by a simple linear equation and the third joint angle q_8 is approximately constant (Figure 8). We use the interpolated joint angle to control TATOR II using a PD control law and we simulate its motion for the crawl posture(Figure 9). According to (R.M.ALEXANDER, 1984) and (S.RENOUS, 1994), the quadruped has eight gaits defined by the relative phase between the legs. We simulate the locomotion of TATOR II for these gaits and we record the distance travelled by the center of mass (Table 1).

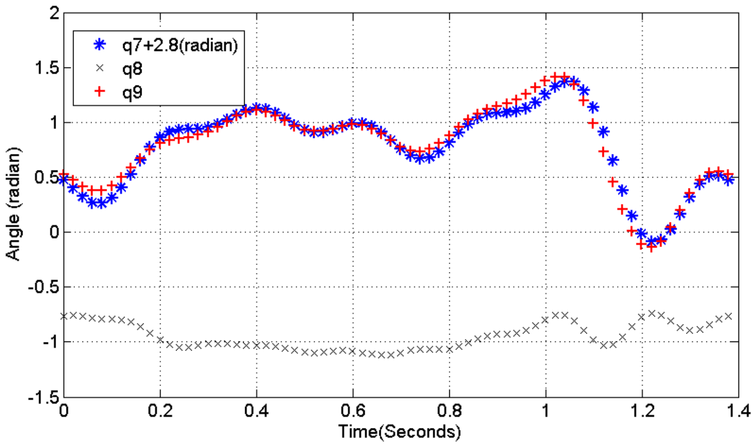

Figure 8. Joint angle q_8; Synergy between q_7 and q_9 two joint angles of the shell-scapula joint articulation

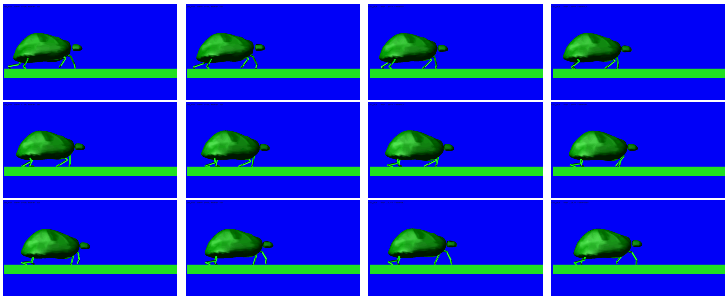

Figure 9. Sequence of a simulation video of TATOR II in crawl posture

Table 1. Distance travelled by the center of mass for the different gaits

Posture	Distance(mm)
crawl	45 mm
trot	62 mm
pace	50 mm
canter	63 mm
transverse gallop	51 mm
rotary gallop	58 mm
bound	43mm
pronk	8.2 mm

4 Conclusion

This paper presents new methods and protocols to create a virtual model of quadrupeds by performing experiments on real animals. Many contributions to the field of bio-mimetic and quadruped robot research are presented in particular:

- an approach to model the kinematics and estimate the motion of a physical terrestrial turtle;
- a new dynamic model of bio-mimetically inspired robot from real animal for simulation and Control;
- Significant experimental results on turtle locomotion and important new conclusions on gates and contact. In particular a synergy between joint angles and a resemblance in locomotion modes between the living subjects used during the experiments. In fact, during the experiences both subject use the hind limb to accelerate and the fore limb to create breaking forces. Experience on a larger number of specimens should be conducted to verify these results.
- A new experimental bench to measure the motion and the contact forces of moving tortoises.

Nevertheless, in this study we control our model by using a position control law; a future perspective is to control it using a hybrid force-position control law (J.Park and O.Khatib, Sept 2008) .

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