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Design Considerations for a Biologically Inspired Compliant Four-Legged Robot

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Abstract— **In this paper we summarize some basic principles of legged locomotion in animals and then discuss the application of the principles to the design and fabrication of a four-legged robot. The here presented model combines ideas for better locomotion of robots both in the biologically inspired, mechanically intelligent structure and in the bionic controller. The movement of the legs is triggered by bionic drives with a setup similarly to biological muscles. The robot is characterized by several different gaits and an animal like locomotion without using feedback control. It has four legs, each having three joints of which two are actuated. During the development we also paid attention to the technical realization of the model. Special techniques to reduce the weight of the robot such as the achievement of different motions by changing the spring stiffness by means of intelligent control instead of an additional motor were also focused on during the development. Two novel features of our four-legged concept comprise the possibility of easily changing the spring stiffness deployed in the bionic drives of the joints and the way of this adjustment which requires neither complex computation nor additional motor. This feature allows the smooth transition to different gaits without necessarily having to change the controller parameters.**

I. Introduction

Animals and humans employ legged locomotion because of the incredible adaptability and versatility this method of locomotion provides. Legs make it possible to move on smooth and rough terrain, to climb stairs, to avoid or step over obstacles, and to move at various speeds.

But walking is a complex process requiring the coordination of numerous muscles to maintain a stable posture while providing forward progression. The remarkable series of coordinated actions require no central control from higher centers, they depend on spinal feedback and large numbers of local control and feedback systems. Stable walking requires the generation of systematic periodic sequences of leg movements at various speeds of progression. At slow velocities it is characterized by static stability, in which the center of mass of the body remains within the polygon of support formed by the legs in contact with the ground. Animals with six or more legs have guaranteed static stability if they leave at least four feet in contact with the ground. The stability of four-legged animals, on the other hand, is conditional on the location of the center of gravity as soon as they lift one leg off the ground. Quadrupeds have active control systems that shift their body positions appropriately to ensure that the vertical projection of their center of gravity onto the support

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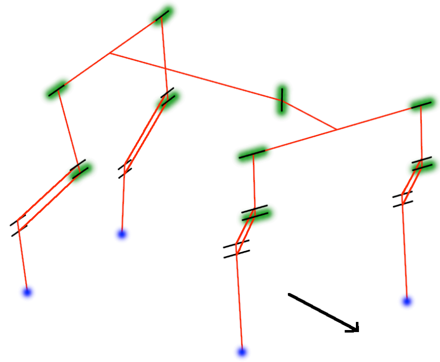

Fig. 1. Overview of the whole structure of the model. The arrow identifies the walking direction.

surface falls within the triangle of support from the legs. The fact that locomotion is possible without central control is evident in quadrupeds with a broken spinal cord [1].

The locomotion of quadrupeds differs both from that of insects and from that of humans in a number of significant ways. As compared to that in humans and other bipeds, static stability in quadrupeds is enhanced by the increased number of support points that result from having four legs in contact with the ground rather than two and by the horizontal posture of the body about its center of gravity. Additionally, quadrupeds are characterized by a number of different periodic sequences of leg movements, such as crawl, walk, trot and canter, which differ in the sequence in which the legs contact the ground. The transition from one gait pattern to another is related to speed and efficiency (energy consumption per unit distance traveled).

Recent developments in legged robots, often based on biological inspiration, have led to significant improvement in their speed and stability. This paper will present and discuss various considerations for the mechanical structure and controller design for a biologically inspired compliant quadruped that is capable of walking on uneven terrain, does not require sensor feedback and demonstrates efficient and versatile locomotion. In Section II we will review existing quadruped models. The principal setup of the kinematic design, actuation, and control are described in Section III. Additionally, the various approaches for underactuated kinematic leg design and especially the link lengths obtained by optimization are discussed in Section IV. By varying diverse control parameters the model is capable of performing various gaits. A graphical view of the developed structure is displayed in Fig. 1.

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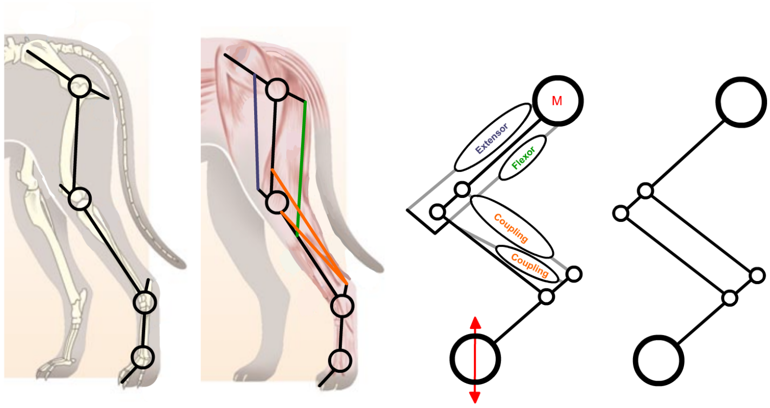

Fig. 2. Skeleton of a shepherd and the pantograph mechanism.

II. State of the Art

A highly nonbiological robot is represented by one of the first developments, Phony Pony from University of Southern California [2]. It has four legs, two joints each (hip and knee). They are identical to one another and the front and back pair are mounted and controlled in the same way. The robot is capable of emulating a number of quadruped gait patterns, including crawl, walk and trot, but at a very slow speed. The machine is not capable of high-speed gaits (such as canter or gallop) in which all four legs may be off the ground for short time intervals. The robot is controlled by a finite-state machine using sensory feedback on the state of its joints, without any internal model of its kinematics or dynamics.

Raibert used the unique inverted-pendulum approach to locomotion for the development of his quadruped [3]. He connected two of his bipeds to obtain a four-legged running machine. Pairs of legs work together, as in trot. The theory of his one-legged hoppers was applied to the quadruped by letting both legs of a pair strike the ground at the same time and leave for the swing portion of the cycle at the same time. This way the control can be considered to be equal to the control of a biped. Each leg has 2 degree of freedoms (dof): one moves the leg forward and backward and the second one changes its length. Also an air spring is deployed within each leg to control compliance in the axial direction.

The realization of simple design of legs is presented by Scout II from McGill University [4]. Each leg has two dofs, but only a single actuator, which controls the active degree of freedom: leg rotation at the hip in the sagittal plane. There is also a passive dof, the compliance of the leg. Each leg is a spring loaded inverted pendulum (SLIP). The SLIP character is influenced by Raibert's work. The control of the robot's motion is largely due to intrinsic mechanical feedback, and there is no active state feedback (like velocity for instance) to ensure stability. The controller consists of two independent virtual controllers, one each for the front and back legs respectively. These controllers detect only two states for the legs: stance and flight (rather than swing), which is analogous to Raibert's view of his monoped.

Puppy from University of Zurich was a running dog project [5]. The design was based on the anatomy of the dog, including joints, muscles, and dimensions. The skeleton consists of 28 passive joints, each of which provides 1 rotational dof. Artificial muscles connect the leg and body segments. An additional six muscles control the neck. The head includes a binocular active vision system, with four servo-motors and two miniature cameras. All motors are controlled by an external computer through a communication interface with microcontrollers. The robot runs with a bounding gait.

In Tekken I and II from University of Electro-Communications in Tokyo developed by Kimura and Cohen central pattern generators (CPGs) play an important role [6], [7]. The implementation of the robot includes a nervous system model with a neural oscillator that provides the robot with some ability to adapt to irregular terrain, both in walking and in running.

Another clearly biologically inspired, with a major emphasis on mechatronic issues, is Warp I from Royal Institute of Technology Stockholm developed by Ingvast [8] designed to walk on rough terrain whereas the AIBO [9] from Sony Digital Creatures Laboratory by Fujita is a clearly conventional and fully actuated robot which has a rich collection of sensors and behaviors. Actuators provide leg, head, and body movements and thus allow the robot to engage in a variety of behaviors.

III. Modeling

A. Kinematic Design

Our developed model consists of stiff rods with connecting possibilities such as hinge joints or ground contact points. Each of the four legs of the model consists of three links, three joints and the ground contact point. A special characteristic of all legs is that they are underactuated: only two of the joints, the hip and knee are actively actuated by actuation modules. The ankle is passively actuated by a pantograph mechanism. If we reduce the rear leg of a dog to its bones, muscles and tendons we obtain the structures shown in Fig. 2. The bones are marked by the lines directly connecting

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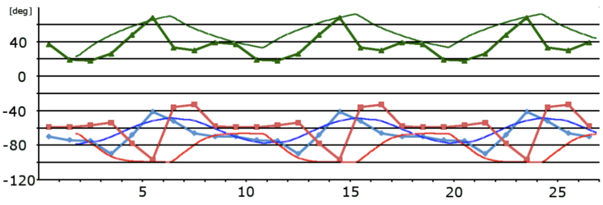

Fig. 3. Comparison of the joint values of hip, knee, ankle of a natural archetype and a simulated model. The smooth thinner lines represent the simulated and interpolated values. The upper picture displays the hip values, the lower the knee and ankle values.

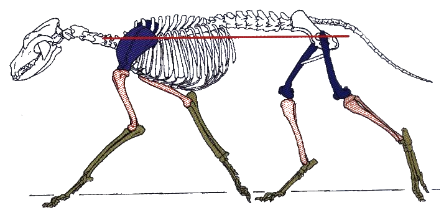

Fig. 4. Skeleton of a Thailand Ridgeback [11].

the joints, the muscles are represented by the parallel lines attached at the hip and knee. In this picture the tendons are coupled at the knee and ankle. Please note that the rear leg of a shepherd is fully actuated. The shown tendon construction thus does not suffice for the complete movement of the lower segments. Therefore, as we aim to construct a biologically inspired four legged robot, we make use of the pantograph mechanism, which is a useful tool to reduce the weights and loads on bones by means of tension band, a technique that is widely used in lightweight design [10]. Replacing the tendons by stiff bars, we obtain the pantograph shown in Fig. 2 at the right. Of course, this way the model looses its elasticity which will be discussed later more in details.

In order to compare the locomotion of a fully actuated and an underactuated robot, the movements of the feet points of both models for several steps were projected onto a two dimensional plane ensuring that both the dimensions and actuation patterns match. Furthermore, the angular velocities of the fully actuated and the underactuated knee and ankle were compared as well, displaying only a slight deviation which is due to the weight change caused by adding the additional rod for the pantograph. Regarding the complete model, though, a global weight reduction can be noticed due to the saving of one motor per leg. Besides, the operating range of the robot can be enlarged by the lower energy consumption. The here shown motion sequence of the fully actuated model match almost exactly the measured real motion sequence of a four legged animal such as a horse as shown in Fig. 3. The real joint values of the hip, knee, and ankle were compared with the simulated ones. Due to the missing load and interpolation there are some deviations between the two plots. However, the fundamental similarity is unmissable.

In order to recognize the fundamental difference between the front and rear legs of a dog for instance, we will have a look at the skeleton of a Thailand Ridgeback in Fig. 4. If we shift the kinematics of the front legs by one level, we can notice that the equally colour-marked bones of the oppositely lying legs are characterized by uniform motion. The horizontal line indicates the pivot points of the topmost rotational motion. Therefore the motion sequence of the front and the rear legs can be said to be equal by ignoring the forefoot but adding a proximal joint, the collarbone. This slight modification has an impact on the length of the segments. While length ratio for the segments of the rear legs is about the same, it is different for the segments of the front legs. It should be also noted that variability among breeds is less then the variability within breeds. Therefore it does not surprise that the length ratio of the collarbone to thigh to shank of the front legs of a shepherd and a Thailand Ridgeback are almost identical with 1 to 1 to 2. In our model the basic setup of the front and rear legs are chosen to be similar. The length ratios are discussed in Section IV.

With the kinematics so far only a movement in the sagittal plane is possible. Movements in the lateral plane become possible by adding a joint as a connecting part between front and rear legs as shown in Fig. 1. This additional joint permits rotations around the z-axis of the height axis. The advantage is that we do not complicate the two dimensional actuation modules in the legs and achieve three-dimensional movements by an additional joint which is responsible for the steering of the whole model. This joint is actuated by an elastic drive that will be explained subsequently.

B. *Biologically Inspired Actuation*

The actuation of the model is achieved by biologically inspired actuation modules which act like muscles. The construction principle of a such bionic drive is inspired by the functional principles inherent to the elastic and antagonistic muscle and tendon apparatus of the human arm [12]. The principle is based exclusively on the application of the series elasticity in the drive in combination with an adequate positioning sensor system. The design therefore only relies on the innovative combination of standard mechanical and electrical components. The elastically driven joint is actuated by a conventional, rotational DC-drive, which is not located at the actuated rotational joint but attached at the other end of the corresponding link [13]. This conventional rotary electric actuator is elastically coupled to the actuated joint by means of a pair of cables and springs. The cables are attached antagonistically to the end of the actuated link, thus relieving the arm from bending stress and enabling a more lightweight design of the link. We will use the above described bionic drives for the actuation of the joints of the model.

C. *Design of a Controller for the Model*

There are centers within the nervous system capable of producing the periodic discharges of nerve impulses associated with walking or various running gaits. They are usually referred to as central pattern generators (CPG) [14]. CPGs are primarily located in the spinal cord. The level of activity of CPG is controlled by higher centers in the nervous system

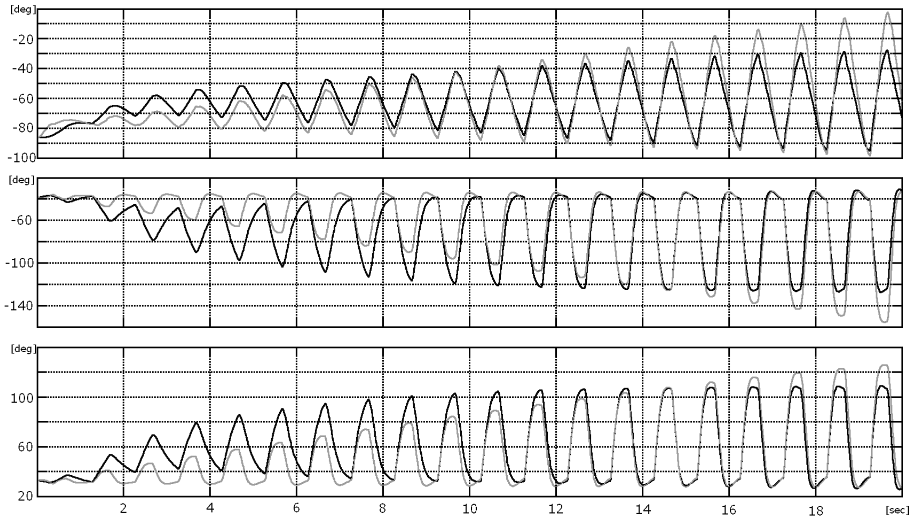

Fig. 5. Comparison of actual and emulated spring stiffness. Black: actual stiffness in the bionic drive for the hip joint. Gray: emulated stiffness in the bionic drive of the hip joint. From top to bottom the joint angles of the hip, knee and ankle are displayed.

and influenced by sensory feedback from peripheral receptors in the limbs. The cerebellum is responsible for fine control of locomotion. In our model we only make use of feedforward control. The model does not require any sensory feedback. The controller is divided into a centralized and decentralized part for each leg. The advantage of such setup is on the one hand exact alignment with the natural archetype and on the other hand increased modularity. During locomotion a living creature consciously controls many parameters such as its velocity, but most actions and mechanical procedures in locomotion are unconsciously made. This control concept is also transferred to the model. The centralized part represents conscious commands, whereas the decentralized part is responsible for all unconsciously taken actions. The central control organ represents a central pattern generator that triggers a sequence of signals for each leg depending on three parameters:

- period: temporal distance between the two signals of a leg. All legs are operated at the same frequency.
- lateral offset: temporal offset of the legs on the same side in percentages with respect to the stride duration.
- caudal offset: temporal offset of the rear legs to each other in percentages with respect to the stride duration.

Each leg is connected to the CPG and receives its own sequence of signals depending on the above parameters. After triggering from the centralized part the decentralized module determines the temporal sequence of joint values. Each joint has two defined states, neutral and active position. If the joints are all in their neutral position, the robot stands still. When a signal reaches a joint, the bionic drive moves the joint by changing the motor position. Since the motor velocities are high, this happens quite quickly. The reaction time of the corresponding segment, however, depends on the spring stiffness of the elastic coupling. The delay can be modeled by a first order lag element. When the signal for the joint ends, the motor spins back. Again the segment follows time-delayed. The proximal joints of the robot differ in their movements from the distal joints. They have an additional state in which they first spin a little back before taking over their active position. This can be observed during animal locomotion.

D. Changing gaits - Emulated spring stiffness

The above described time delay and therefore also the amount of segment movement can not be influenced by the controller parameters. A possibility would be to reduce the motor velocity. Often, however, it is more interesting to control the amount of segment movement, i.e., a segment can spin even further than the motor actually allows. This is of course only achievable in structures where there is an elastic coupling of motor and segment. The biological leg allows such overspinning by the biological configuration of several muscle groups of which some are redundant and have different spring stiffness. This stiffness can be adjusted to each operation. Exchanging manually the springs in the bionic drives of the robot for each different gait is not feasible. The option to implement a second motor for prestressing of the spring is also neither interesting nor attractive since this would result in nine additional motors for the whole robot and therefore lead to an increase in weight. An alternative to the real adjustment of the spring stiffness represents a different triggering of the motor. During trotting for instance, one stride length is not enough to transfer the displacement of the motor to the attached segment. The actual displacement amounts only about half of the preset position before the motor spins back into its neutral position. The emulated spring stiffness allows the same motion sequences as if the spring stiffness was modified by exchanging the spring. It controls the amount to which the motor really should spin. If the emulated spring stiffness is higher than the stiffness of the actually obstructed spring, the motor can reach a higher displacement. To test the concept we used a simple model consisting of a leg of the same kinematic design. In Fig.

TABLE I

NOTATION OF INPUT AND OUTPUT VARIABLES FOR THE COMPUTATION OF EMULATED SPRING STIFFNESS.

Input Variables		Output Variables	
a	active position	α	active position after correction
n	neutral position	ν	neutral position after correction
p	preset position	π	preset position after correction
s	actual stiffness	σ	actual stiffness

5 emulated and actual stiffness are compared. The model with the emulated stiffness is represented by the gray color, the model with the actually changing spring stiffness by the black color. The plots show the joint angles of the hip, knee and the ankle. The stiffness was changed linearly and amounts 0 N/m at the beginning and 20 N/m after $t = 20$ sec. As can be easily recognized there is only a small deviation between the actual and emulated stiffness. Consequently the desired effects can be achieved without manually exchanging springs corresponding the currently required stiffness. In the following we present a methodological approach for the use of emulated stiffness. The variables needed for the triggering of the controller are defined in Table I. The equations used for the computation of the active, neutral, and preset position and actual stiffness is computed as follows:

$$\alpha = \mu * \frac{a-n}{s} + n + o \quad (1)$$

$$\nu = n - \mu + o \quad (2)$$

$$\pi = \mu * \frac{p-n}{s} + n \quad (3)$$

$$\sigma = s\,, \quad (4)$$

where μ represents the emulated stiffness. o stands for the offset and amounts $o = 10$. Its addition in Equation (1) and (2) is empirically based and serves as a better adjustment of the emulated to the actual stiffness particularly in the relevant intervall of 8 N/m to 16 N/m . The computation of the preset position is only necessary when emulated stiffness is also deployed in the bionic drive for the proximal joints. In order to test the emulated stiffness more in details we conducted further tests which, however, can not be described here due to the limited number of pages. The results of the experimental tests confirm that different gaits can be achieved only by virtually changing the spring stiffness.

E. Structure of the Model

The final structure of the model is shown in Fig. 1. The model consists of nine joints in total, two in each leg and one for the movement around the body z-axis. The marked joints represent the actuated ones. The two parallel lines in each leg mark the pantograph. The feet of the legs are modeled as points indicating the location of ground contact.

The here presented model used as basis for the described experiments and tests combines ideas for better locomotion of robots both in the biologically inspired, mechanically intelligent structure and in the bionic controller. One special feature of this model is certainly the integrated possibility of emulated stiffness, i.e., adjustment to motions that require a different stiffness than actually deployed. The deployment of emulated stiffness as well as the activation of the segments by wire rope hoists deployed in the bionic drives are counted among the novelties of the proposed robot model. It is also worthwhile to consider the ground contact model which allows movement in three dimensions and also computes the necessary adhesive force and sliding friction data. It also allows the consideration of height functions for the investigation of the walking behavior on uneven terrain. Focus also lies on the development of a lightweight robot to reduce the energy consumption.

TABLE II

COMPARISON OF DIFFERENT LEG STRUCTURES. THE UNIT OF SPEED IS m/sec, ENERGY CONSUMPTION IS MEASURED IN $\sum \delta p/m$ WHERE p STANDS FOR POSITION, INCLINATION IS GIVEN IN %.

Leg kinematics	Speed	Energy Consumption	Stair	Up-Down	Inclin.
fully actuated	0.7	631.7	yes	yes	10
stiff pantograph	0.5	407.8	yes	yes	35
stiff cross-pant.	0.7	347.7	yes	yes	25
elastic pant.	0.2	1146.0	no	no	0
elastic cross-pant.	0.4	744.3	no	no	5

IV. SIMULATION AND OPTIMIZATION RESULTS

As we have already seen, both the locomotion by means of the described drives and kinematics and the variation of gaits work quite well. Although the robot is not feedback controlled it is capable of moving stably even on uneven ground and adjusting its movements by itself when colliding with obstacles. This property of mechanical systems is also known as mechanical intelligence [5]. Surely the deployment of feedback control will increase the robustness of a such model.

In order to find an optimized structure, different locomotion mechanisms inspired by natural archetypes have been compared. In each test a pair of legs with the same kinematics is analyzed. For the simplification of the tests only two dimensional movements are allowed. We compared basic properties, the average speed and energy efficiency, given the same controlling parameters and dimension of the leg pairs. Furthermore, we tested the walking behavior in the presence of obstacles. Obstacles were represented by stairs of 16 cm of height, and a combination of 10 % ascent and descent and an inclination that continuously gets steeper. The results of the four best leg kinematics can be found in Table II. The results of a fully actuated model are displayed for comparison reasons as well. To better understand the underlying kinematics, the leg models are shown in Fig. 6. The selected leg kinematics are given the following names based on their structure:

- stiff pantograph: pantograph with stiff rod,
- stiff cross-pantograph: cross-pantograph with stiff rod,
- stiff cross-pantograph: pantograph with elastic connection elements, and
- elastic cross-pantograph: cross-pantograph with elastic connection elements.

Due to its simplicity and high robustness, good optimization possibilities and closeness to the natural archetype, the stiff

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TABLE III

COMPARISON OF DIFFERENT PROPORTIONS OF SEGMENT LENGTHS, WHERE T STANDS FOR THIGH, S FOR SHANK AND F FOR FOOT. THE UNIT OF SPEED IS m/sec, ENERGY CONSUMPTION IS MEASURED IN $\sum \delta p/m$, INCLINATION IS GIVEN IN %.

Proportion t:s:f	Speed	Energy Consumption	Inclin.	Distance
1 : 1 : 1	0.6	401.6	32	4.379
4 : 5 : 5	0.5	407.8	35	3.714
4 : 5 : 4	0.48	426.1	36	3.916
4 : 5 : 2	0.5	419.7	32	4.157
4 : 4 : 5	0.65	366.7	34	5.051
1 : 1 : 2	0.55	410.8	45	4.120

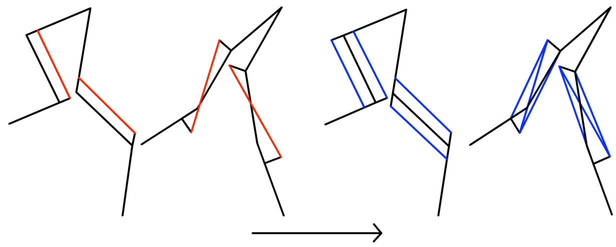

Fig. 6. Comparison of the best four leg kinematics. From left to right: pantograph with stiff rod, cross-pantograph with stiff rod, pantograph with elastic connection elements, cross-pantograph with elastic connection elements. The arrow indicates the walking direction of the leg pairs.

pantograph structure turns out to be the most appropriate for the leg design. In order to increase the speed of the robot and to simultaneously reduce the energy consumption, it is possible to select the stiff cross-pantograph in which a lever serves as gear for enlarging the movements. The problem, though, is that the model decreases in robustness as can be seen in Table II: the climbing power becomes smaller. We also examined elastic structures. In case of high spring stiffness the elastic structures behave like pantographs with stiff rods and in case of low spring stiffness the dynamics of the model deteriorates.

After the selection of the kinematics the segment lengths were to be optimized. Like the natural archetype the robot model possess the same kinematics in the rear and front legs. Only the proportions of the segment lengths differ. The experimental setup was the same as before for the kinematic structure. All pairs of legs had to accomplish a test track including obstacles such as stairs, combination of ascent and descent and an inclination that continuously gets steeper. As kinematic structure we used the prior optimized stiff pantograph. The results are shown in Table III. Since the front legs are important for steering of the model they were examined more in details. After optimization the values of the segment lengths were surprisingly almost the same as is the case in the front legs of the Thailand Ridgeback.

V. CONCLUSION

The investigations described in this paper showed that the proposed model for a four-legged robot is capable of various gaits and moves as dynamically as an animal does. The mechanical intelligence of the model allows for a sophisticated approach without the need of feedback control and can therefore be considered as distinctive feature. By changing the controller parameters it is possible to let the model walk various gaits. Emulating the spring stiffness in the bionic drives of the legs can be efficiently used for changing the gaits of the robot. The movement in the lateral plane is enabled by a steering module designed similarly to the backbone of an animal. The results of the optimization of the segments lengths demonstrate quite impressively that the extracted data from natural archetypes can directly be taken over or used as good starting values for the optimization process. The use of the bionic approach is thus quite helpful not only for finding ideas for the principle and functional studies. It is clear that a final validation is only possible after evaluation of the constructed model. Consequently, the simulation studies lay the foundations for the construction of a dynamically moving and biologically inspired four-legged robot that can autonomously change the spring stiffness of its bionic drives highly efficiently.

REFERENCES

[1] G. A. Bekey, *Autonomous Robots: From Biological Inspiration to Implementation and Control*. Cambridge, Massachusetts: The MIT Press, 2005.

[2] A. A. Frank, "Automatic control synthesis for legged locomotion machines," Ph.D. dissertation, Department of Electrical Engineering, University of Southern California, Los Angeles, 1986.

[3] M. H. Raibert, *Legged robots that balance*. The MIT Press, 1986.

[4] I. Poulakakis, J. A. Smith, and M. Buehler, "On the dynamics of bounding and extensions toward the half-bound and the gallop gaits," in *Proceedings of the Second International Symposium on Adaptive Motion of Animals and Machines*, 2003.

[5] F. Iida and R. Pfeiffer, ""Cheap" rapid locomotion of a quadruped robot: Self-stabilization of bounding gait," *Intelligent Autonomous Systems*, vol. 8, pp. 642–649, 2004.

[6] H. Kimura, S. Akiyama, and K. Sakurama, "Realization of dynamic walking and running of the quadruped using neural oscillator," *Autonomous Robots*, vol. 7, no. 3, pp. 247–258, 1999.

[7] Y. Fukuoka, H. Kimura, and A. H. Cohen, "Adaptive dynamic walking of a quadruped robot on irregular terrain based on biological concepts," *The International Journal of Robotics Research*, vol. 22, no. 3-4, pp. 187–202, March-April 2003.

[8] J. Ingvast, C. Ridderström, F. Hardarson, and J. Wikander, "Warp1: Towards walking in rough terrain - control of walking," in *International Conference on Climbing and Walking Robots (CLAWAR)*, 1993.

[9] M. Fujita and H. Kitano, "Development of an autonomous quadruped robot for robot entertainment," *Autonomous Robots*, vol. 5, no. 1, pp. 7–20, 1998.

[10] H. Witte, M. S. Fischer, N. Schilling, W. Ilg, R. Dillmann, M. Eckert, and J. Wittenburg, "Konstruktion vierbeiniger Laufmaschinen anhand biologischer Vorbilder," *Konstruktion*, vol. 9, pp. 46–50, 2000.

[11] (2009, Aug.) Thailand - ridgeback. [Online]. Available: http://www.vomcrownhill.com/Standard.html

[12] B. Möhl, "Bionic robot arm with compliant actuators," in *Proc of SPIE - Sensor Fusion and Decentralized Control in Robotic Systems III*, vol. 4196, October 2000, pp. 82–85.

[13] S. Klug, T. Lens, O. von Stryk, B. Möhl, and A. Karguth, "Biologically inspired robot manipulator for new applications in automation engineering," in *Proceedings of Robotik 2008*, ser. VDI-Berichte, no. 2012. VDI Wissensforum GmbH, June 2008.

[14] S. Grillner, "Control of locomotion in bipeds, tetrapeds, and fish." in *Handbook of physiology*, V. B. Brooks, Ed. American Physiology Society, 1981, vol. 1, pp. 1179–1236.