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Concept Evaluation of a New Biologically Inspired Robot "LittleApe"

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Abstract— **In this paper we present a concept and an evaluation of an ape-like robot which is quite similar to its biological model. Aim of our project LittleApe is to build a small and extreme lightweight robot that is capable of walking on two and four legs as well as of changing from a four-legged posture to a two-legged posture, manipulating small objects, and which is also able to climb. LittleApe is modelled with attributes of a chimpanzee regarding limb proportions, spinal column, centre of mass, walking pattern, and range of motion.**
The concept of LittleApe is tested in simulation while building the real system. Two aspects were chosen to evaluate the concept described in detail within this paper. The first aspect comprises the use of an evolutionary method and the comparison of different morphologies. Based on the results from the first one, the second aspect deals with the manoeuvrability of the LittleApe robot.

I. INTRODUCTION

Legged locomotion has advantages over wheeled or tracked locomotion in terrain that is difficult to access. One field of research in the area of biologically inspired robots deals with robots which are able to climb. Robots like RisE [6][19] or StickyBot [10][16] have the ability to walk on flat ground and climb on vertical surfaces. Both robots use bio-inspired methods for climbing. Rise has six feet with an embedded microspine structure at each foot while StickyBot uses the principles of adhesion to climb.
The project ARAMIES [22] was the development, construction, and testing of a four-legged walking robot which is able to climb in steep slopes with the aid of a tethering system. The system is capable of moving stably on level ground and, using its actuated claws, of climbing rung walls of up to 70° inclination.
GoRobot [23] [24] is able to walk on four legs and to stand on two. But unlike GoRobot, LittleApe will have a power supply and the hardware controller on-board.
LittleDog [1][12] is another biologically inspired robot whose size better fits to the presented robot. The robot is not climbing but it is capable of negotiating obstacles of about 40 % height difference of its leg length. Nevertheless, systems that change from a four-legged posture to a two-legged posture and walk adequately with two and four legs are rare.
In this paper, a concept for a four-legged robot is introduced. The concept is derived from the biological antetype, the chimpanzee (*Pan troglodytes*), by extracting the main physical properties. The robot and especially the chosen properties are evaluated by the use of simulation tools and evolutionary algorithms.

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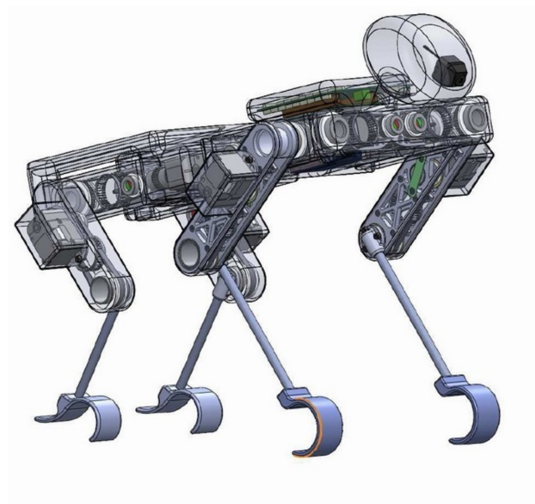


Fig. 1. CAD sketch of the robot LittleApe

An ape-like robot is a suitable experimentation platform with a high spectrum of motion options. Differences in the possibilities of motion and manipulation can be represented clearly. Its physiological structure makes it possible to let it run in unstructured areas on four legs. Because of the short rear legs and the long front legs (see fig. 1), it will be able to sit down smoothly. While sitting (see fig. 8) in a stable posture or if the robot stands on two legs it has the potential to manipulate smaller objects with the forelimbs. In a two-legged posture, this kind of system has e.g. the possibility to look over obstacles which are higher than itself in a four-legged posture. Thanks to the versatility of the movement form, overcoming obstacles, which are higher than the robot standing on four legs, is just as possible as climbing on certain fences. The possibilities of motion and different behaviours are more variable than in robots which are specialised on one movement pattern only.

II. BIOLOGICAL INSPIRATION

A. Proportions

The lengths of the body segments of LittleApe are proportional to those found in *Pan troglodytes* [2]. For better comparison, extremity lengths were normalized with trunk length (tab. I). These natural proportions are essential for a realisation of lifelike locomotion patterns and strain distributions. In chimpanzees and bonobos, the effective length of the forelimb is increased by the length of the palm and parts of the fingers (see table I, also shown in fig. 2).

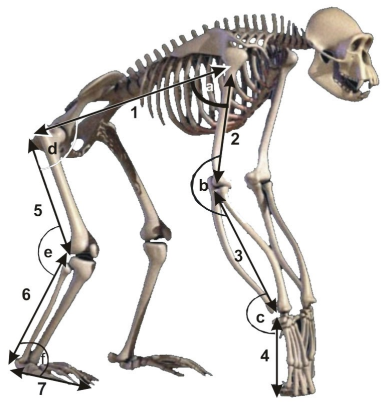


Fig. 2. *Pan troglodytes* (chimpanzee) in a quadrupedal posture. Numbers 1 - 7 identify segments; Characters a - f identify joints. 1: trunk, 2: upper forelimb, 3: lower forelimb, 4: hand (length from joint centre to the ground), 5: upper hindlimb, 6: lower hindlimb, 7: foot; Illustration courtesy of [18]

TABLE I
NORMALIZED AND ROUNDED SEGMENT PROPORTIONS IN CHIMPANZEES [2]

Segment	Number in Fig. 2	Normalized length
Trunk	1	1
Upper forelimb	2	0.5
Lower forelimb	3	0.5
"Hand"	4	0.3
Upper hindlimb	5	0.5
Lower hindlimb	6	0.5
Foot	7	0.4

B. Mass and Force Distribution

1) Body: In contrast to other quadrupedal vertebrates, primates carry most of their weight on their hindlimbs although their centre of mass lies closer to their forelimbs [14]. This force distribution is obtained by constant muscle activity in the hind limbs. These "retractors" lift the trunk, induce a torque around the hip joints, and unload the forelimbs [13]. Unloaded forelimbs have several advantages: they are free to manipulate objects, and a weight shift to the hind limbs is supposed to be one of the first steps to an upright posture and bipedalism [14].

2) Extremities: In a limb, the moment of inertia is reduced by a proximal (close to the body) centre of mass [8]. In LittleApe, we make use of this basic biological principle; hence the approximated mass distribution of *Pan troglodytes* [2] was realized in the simulation. In quadrupedal vertebrates, the centre of mass is shifted by a proximal position of heavy muscles. Muscle force has to be transmitted to the joints via tendons. For the robot's actuator a similar layout is designed.

C. Posture and Range of Motion

The habitual posture of a quadrupedal standing chimpanzee can be seen in fig. 2. Corresponding joint angles and the range of motion during bonobo locomotion at walking speed [3] are shown in tab. II. Chimpanzees, bonobos, and other primates show a special locomotion behaviour called knuckle walking. Here, weight is supported not by the complete hand, but only by the dorsal side of the middle phalanges. While walking, due to muscle activity, the hand and wrist configuration is quite rigid. The fingers are positioned in a very compact way and special fat pads on the phalanges provide further bearing and damping. As a result, the fragile fingers are protected optimally and can be used to manipulate when not used for locomotion [9].

TABLE II
JOINT ANGLES WHILE QUADRUPEDAL STANDING AND RANGE OF MOTION.

Joint	Character in Fig. 2	Joint angle [°] standing posture	Range of motion [°] while walking[3]
Shoulder	a	50	-
Elbow	b	135	-
Wrist	c	180	-
Hip	d	100	60 - 120
Knee	e	140	60 - 140
Ankle	f	60	50 - 95

D. Locomotion Pattern

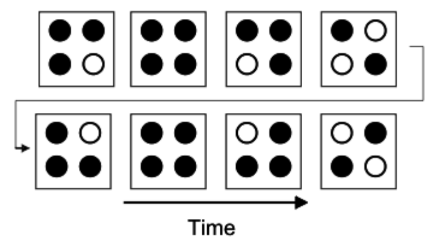


Fig. 3. Most common walking pattern, black dots indicate ground contact

Hildebrand [7] describes 18 different gait patterns that are used by primates. In the scheme of names suggested by Hildebrand, the primate gaits are classified as "diagonal sequence, diagonal couplets gaits". The most common walking pattern is shown in fig. 3. This pattern includes phases of dynamic stability and differs from walking patterns that are normally chosen for robots.

III. DESIGN AND CONTROL OF LITTLEAPE

A. Technical Specifications

Each leg has three active joints, LittleApe has altogether 12 DOFs. The first actuator moves the leg sideways, so the foot can either move under or away from the body to stabilise the robot (y-axis in fig. 4). Both the second and third joint are moving in the same direction. They can be used to walk forward or backward (x-axis in fig. 4). LittleApe uses digital actuators which provide among other things a feedback of the angular position.

LittleApe has a total weight of 2 kg including the rechargeable battery pack, controller, communication modules, and sensors. With a height of about 38 cm in front and 29 cm in rear, the normalized proportions with 1.3:1.0 are equal to those observed in *Pan troglodytes*. Fig. 4 displays the LittleApe Robot in simulation. The numbers identify the segments.

A timing belt transmission will be used to connect the

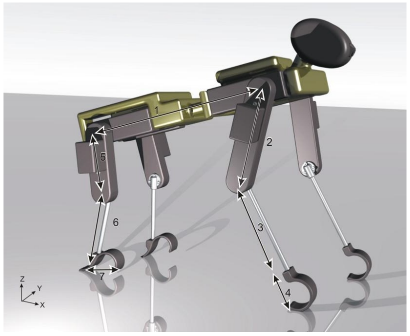


Fig. 4. LittleApe in a quadrupedal posture. The numbers that identify the segments are equal to those in fig. 2

servo motor to the joints of the robot. Separating the motor from the joint and connecting it with a timing belt provides advantages like moving the actuator upwards to the body which will help to keep the inertia of the leg low and will reduce the dimensions of the knee joint. The timing belt transmission features a 3:2 gear reduction which increases the output torque to 1.95 Nm while reducing the range of motion to 200 degrees. The actuator design provides a position and torque measurement.

The design of the legs is like an inverted pyramid with most of the weight on top of the leg near the body and getting lighter approaching the foot.

A hand is developed and built for LittleApe which is based on an ape's hand while walking. With this hand, the robot should be able to walk and to climb. Unlike a real ape, the hand is currently not actuated.

B. Simulation Environment

Machina Arte Robotum Simulans (MARS) is a simulation and visualisation tool for developing control algorithms and designing robots. It consists of a core framework containing all main simulation components, a GUI, OpenGL based visualisation, and a physics core that is currently based on ODE. MARS is intended to provide a tool chain from creating objects up to their simulation and visualisation. The created objects can be controlled via a dynamically loadable controller, or a socket communication protocol. The graphics can run without physics and vice versa. Additionally, a communication module is implemented and it is possible to include customized controllers for a robot. Covariance Matrix Adaptation - Evolution Strategy (CMA-ES) [5] is an advanced form of evolution strategy [17] that can perform efficient optimization even with small population sizes. Each individual is represented by an $n-$dimensional real-valued solution vector. The combination of MARS and CMA-ES has been used in our institute to learn walking patterns and robot morphology [15].

The actuators in simulation have the same limitations regarding speed and force as the real actuators. All components are simulated with the real weight.

C. Control

For the control of our robot and to realise the movements, the micro kernel Monster [20], [21] is used. Robots like Scorpion or Aramies use Monster already [11], [22].

Thus, we can use a biologically inspired locomotion approach. The concept comprises continuous rhythmic locomotion signals as well as postural activity which is generated by a model spinal central pattern generator in vertebrate systems [4]. For technical implementation, only three parameters (amplitude, frequency, and offset) are necessary to change the rhythmic movement.

With feedback from the torque measurement, a dynamic load distribution could be implemented that keeps the centre of mass within the support triangle of the legs.

IV. EXPERIMENTAL CONCEPT EVALUATION

Initially, we deal with two criteria to evaluate the robot. The main aspect has a priority in energy-efficient walking. Based on the results from the first one, the second step deals with the manoeuvrability of the robot. Typically, a four-legged robot is designed with four identical legs. Shoulder and hip have the same size, but LittleApes proportions are not symmetric.

A. Experiment 1 Set-up

As mentioned before, we firstly focused on energy-efficient walking. With the CMA-ES, an evolutionary method is used to evaluate the walking behaviour. In order to assess the evolved walking patterns, a fitness function is used (see function 1) which is calculated with following variables measured in the simulation: The distance travelled d, the average torque τ and average load l of the joints, and an indicator if other parts of the robot than the feet have ground contact. The fitness function is defined as sum of three terms. The first term $\frac{\tau}{d}$ assesses the energy efficiency, i. e. the energy consumed for the covered distance. The second term $\frac{l}{d}$ is based on the load incurred on the joints over the covered distance. The third term $1000g$ checks whether parts of the robot other than the feet come into contact with the ground and a strong negative reward is added if that is the case. At first sight, the second and third term are not directly related to the energy efficiency, but the second term deals with the bracing of the system. Stress on the structure comes along with abrasion of the hardware. With a high abrasion it cannot produce an optimal behavior.

If there is no negative reward like in term three, we run the risk of the robot rolling instead of walking, in order to get a good ratio between distance travelled and average torque.

$$fitness = \frac{\tau}{d} + \frac{l}{d} + 1000g \quad (1)$$

The lower the fitness value the better is the result. Each evolution process (during which several populations are generated) proceeds until the `sigma` value of a population is less than 0.01. `sigma` is an internal value of CMA-ES which is equivalent to the convergence of an evolution process.

For each individual, the fixed start position is predetermined. Before the robot is reset into the world, its starting posture is calculated and adapted to the start position. So individual `n` has the same start conditions like individual `n-1`.
Equal for all walking patterns is the use of a crosswise walking pattern depicted in fig. 3. The time shift between the right rear leg and left front leg as well as between the left rear leg and right front leg is around 10 % of the time a complete step cycle require.
In the following, three morphologies are compared. Morphology 1 is an ape-like morphology with short rear legs and long front legs. In the second one, all legs have the same length, the rear legs were extended to the same length as the front legs. To answer the question whether there is an advantage in using stronger motors proportionally to the weight, we increased the speed and the force by factor 1.5 of the actuator for the ape-like morphology (morphology 3). To get a significant data-set, 50 evolutions with each of the three variations are made.

B. Learning Parameters

The CMA Evolution Strategy was used to learn an energy-efficient walking pattern for the robot. Due to the given morphology and shift phase between the legs, parameters like height of the robot, offset x-axis of the feet, scaling of amplitude of the leg movement, scaling the height of the swing movement, time scaling of the locomotion, and the body pitch had to be evolved. Table III shows the parameter set, the start values of the parameters, and the maximum variance of the start values for the evolutionary algorithm.

TABLE III
START VALUES OF THE PARAMETERS AND RANGE OF MOTION.

Parameter	Start value	Max. variance
Height of the robot	20 cm	±10 cm
Offset x-axis front feet	0 cm	±10 cm
Offset x-axis rear feet	0 cm	±10 cm
Scaling of amplitude	100 %	+200 %
Scaling the height during swing	100 %	+200 %
Time scaling of locomotion	1 sec. per step	±50 %
Body pitch	0.0°	±50°

C. Classification Experiment 1

After the evolutionary process, the results were classified in three categories (see tab. IV). The first category combines all evolutions where the body degree is positive and higher than 5°, so the posture equates the posture of the antetype where the shoulder is higher than the hip. In the second category, the body is parallel to the ground and the body pitch between -5° and 5°, and the third category combines all evolutions with a negative body pitch less than -5°. Note that the classification is unequal to the morphology.

Table V shows the average values of the morphologies with each category regarding the average number of individuals, the average angle of the body, the average fitness value, and the best fitness value found at the individuals. The used number of values to calculate the averages can be found in tab. IV.

TABLE IV
RESULT FROM THE EVOLUTIONARY PROCESS ARRANGED BY MORPHOLOGIES

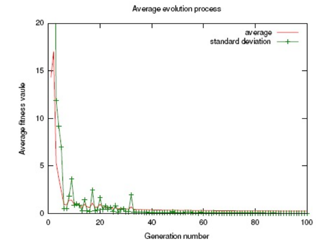
Morphology	Category 1	Category 2	Category 3
Morphology 1	35	11	4
Morphology 2	16	30	4
Morphology 3	32	2	16

TABLE V
RESULTS FROM THE EVOLUTIONARY PROCESS

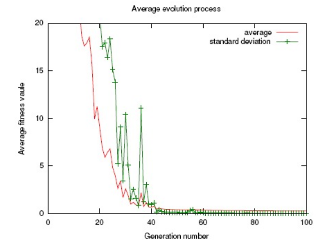
Morphology	⊘ number individual	⊘ body angle	⊘ fitness value	Best fitness value
Morphology 1				
Category 1	1615.71	14.75	0.242	0.237
Category 2	1775.45	-0.1	0.274	0.258
Category 3	2882.5	-8.23	0.245	0.241
Morphology 2				
Category 1	1887.5	8.41	0.258	0.251
Category 2	2060.33	1.79	0.263	0.257
Category 3	2267.5	- 6.87	0.274	0.267
Morphology 3				
Category 1	1437.81	23.25	0.265	0.255
Category 2	2005	0.71	0.338	0.327
Category 3	1690.63	-12.07	0.319	0.314

D. Analysis Experiment 1

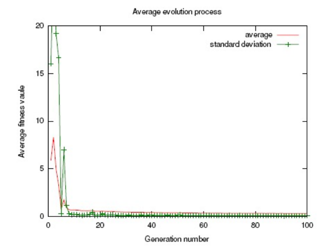
Tab. IV shows that there are only two results for category 2 in morphology 3. So the average values for this combination in tab V are not significant. Not considering these values, one can see that morphology 3 converges in the other categories faster than the other morphologies. Because of the stronger motors it is possible that the walking pattern is (as compared to morphology 1 and 2) more rapidly stable.
Fig. 5 show the average fitness value of all evolutions for each morphology. To give a better resolution, the average fitness value (y-axis) and the generation number have a range from 0 to 20 and from 0 to 100, respectively. Each generation contains 10 individuals. Morphology 1 shows, like morphology 3, quite fast a tendency to reach good fitness values, but unlike morphology 3, has some small outliers. Morphology 2, however, converges significantly later.
Category 1 converges in average more rapidly than category 2 and 3. Contemplating the average fitness values and best fitness values for each morphology, one can see that for each morphology category 1 has the best values. By comparing the morphology 1 with 3, it can be seen that morphology 1 needs for category 1 more individuals than morphology 3, but has better fitness values. Caused by results from the way of calculating the fitness function, where individuals with a low energy consumption per covered distance get a better fitness value, morphology 1 develops a better walking pattern which, however, is more time-consuming.
Category 2 has significantly more members for morphology 1 than for morphology 3, while category 3 has more members in morphology 3. With the stronger motors it is possible to



(a) Average fitness value of all evolutions of morphology 1



(b) Average fitness value of all evolutions of morphology 2



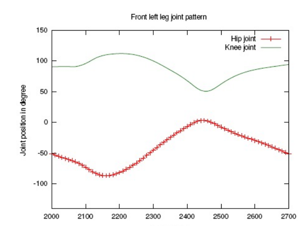
(c) Average fitness value of all evolutions of morphology 3

Fig. 5. Average fitness value for each morphology of all evolutions

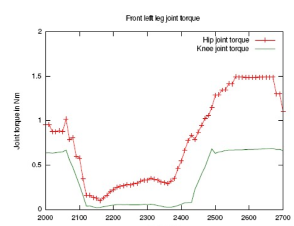
get good fitness values while walking with a negative body pitch.

It can be seen in comparison to the other morphologies that morphology 1 has in the first and third categoric the best fitness values. The first morphology with the first category has the best fitness value in average and also altogether, which brings us to the conclusion that our ape-like morphology is suitable to construct a four-legged robot.

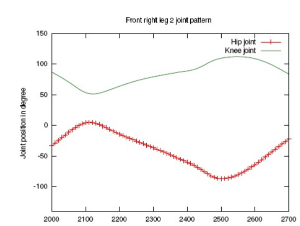
E. Example Result



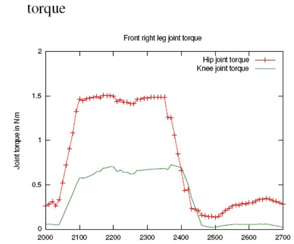
(a) Leg front left, the second and third joint pattern



(c) Leg front left, the second and third joint torque



(b) Leg front right, the second and third joint pattern



(d) Leg front right, the second and third joint torque

Fig. 6. Joint and actuator torque curves for the front legs while walking

Through the evolutionary method, by changing the parameter set, different walking patterns were evolved which differ in height during the stance phase, the speed of the movement, the height and angle of the body, and the stride length. One in comparison to the other morphologies stable and energy-efficient walking pattern from morphology 1 is chosen and shown in fig. 7. In fig. 6, the joint curves and the torque curves for the front legs for one step are displayed. The first joint was not used for this walking pattern, so it is not plotted in the graphs. The x-axis shows the time in seconds. On the y-axis the angular movement and the torque are displayed in degrees and in Nm, respectively.

The sequence in fig. 7 shows the robot walking in simulation. While walking with one of the best walking patterns,

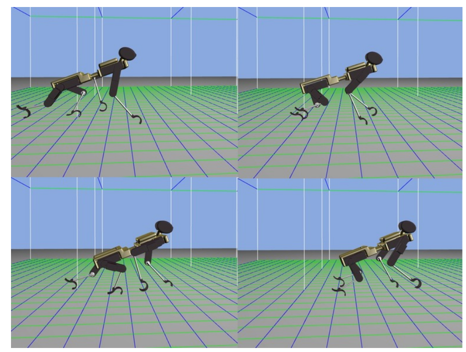


Fig. 7. LittleApe walking in simulation

the shoulder is higher than the hip. With this walking pattern, LittleApe covers a distance of around five meters in ten seconds. Here, the offset of the x-axis front feet is 6 cm, the offset x-axis rear feet is -1 cm, the scaling of amplitude is 290 %, the scaling the height during swing is 106 %, the time scaling of locomotion 0.7 sec. per step, and the body angle is 20°.

F. Experiment 2 Set-up

The second experiment deals with the manoeuvrability of the robot. It will be evaluated whether the robot has the ability to sit down smoothly. For this aspect, it is not necessary to use evolutionary methods. To get up to the standing posture, two ways are conceivable. Firstly, the robot gets directly from a four-legged posture to a two-legged posture or, secondly, it is sitting down before it stands up. The second case is probably more stable, but has the precondition that the robot is able to sit down. This is why we evaluate a sit-down behaviour.

G. Results Experiment 2

The sequence in fig. 8 shows the sit-down behaviour of the LittleApe robot. As expected in the beginning, because of the morphology it is possible to let the robot sit down smoothly. Consequently, LittleApe can manipulate small objects while it is in a stable posture, or use both hands in a coordinated manner to accomplish a given task. In addition, as mentioned above, a precondition for the stand-up behaviour is fulfilled. The plot (see fig. 9) shows the joint angles during the sit-down behaviour. The marked lines within the plots match the specific pictures in fig. 8. The ground was set slippery for the plot. With more ground friction, the robot has to scuttle with the front legs during the behaviour.

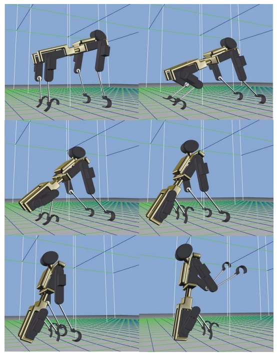


Fig. 8. LittleApe performs a sitting behaviour in simulation

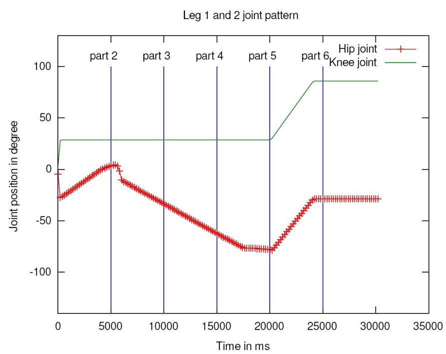


Fig. 9. The movement pattern for sitting down (front legs).

V. CONCLUSION AND FUTURE WORKS

In this paper, we presented a robot that is designed similar to the biological antetype. We chose the ape as antetype because of the large possibilities of motion and manipulation. Firstly, with the morphology we are able to walk in a stable manner, energy-efficiently and fast. Secondly, because of the short rear legs it is possible to sit down to perform manipulating tasks while being in a safe posture, or to stand up. Third, we expect the robot to stand up more easily since the body is not parallel to the ground like many other four-legged robots but in a standing posture about 20 degree tilted. After building the robot, we will investigate the dynamics of our joint and include an accurate model of the system in the simulation.

In future, more walking patterns, a gait transition between these patterns, and a climbing behaviour will be implemented.

Also, an extension of the control approaches increasing the deliberative components and concurrently decreasing the reactive components is planned. With such a robot, which is capable of changing its posture, we want to investigate how an architectural approach may look which allows the robot to change autonomously between these systems regarding the locomotion control.

VI. ACKNOWLEDGMENTS

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