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IMPLEMENTATION OF A QUADRUPED ROBOT PRONKING / BOUNDING GAIT USING A MULTIPART CONTROLLER

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ABSTRACT

This paper presents a multipart pronking/ bounding controller for a quadruped robot, as well as the corresponding experimental results. The controller achieves given apex height and forward velocity in a quadruped robot with only one actuator per leg. A quadruped is designed and built and described in some detail. Experimental results obtained using internal sensors and high-speed camera captions show that the implemented quadruped robot performs pronking gaits and achieves bounding gaits with the desired characteristics.

NOMENCLATURE

x CoM horizontal position.
y CoM vertical position.
θ Body pitch angle.
l Leg length.
γ Leg absolute angle.
γ_{sum} Sum of leg absolute angles.
γ_{dif} Difference of leg absolute angle.
k Leg spring stiffness.
J Dimensionless inertia of the robot body.
I Body inertia.
m_b Body mass.
m Total robot mass.
d Hip joint to CoM distance.
b Viscous friction coefficient.
g Acceleration of gravity.
m_l Leg mass.
I_l Leg inertia.
l_l Leg CoM to hip distance.
$\gamma_{b,td}$ Back leg touchdown angle.
$\gamma_{f,td}$ Front leg touchdown angle.
τ Hip torque.
T_{st} Stance duration.
f As index: front leg.
b As index: back leg.
td As index: value at touchdown.

INTRODUCTION

The transversal of rough terrain and the small footprint requirements in many applications can be met by the development and use of legged robots. Although legged machines have the potential to outperform wheeled vehicles on rough terrain, they

[1] Work completed while at the National Technical University of Athens.

are subject to complex motion control challenges and to balance-in-motion constraints. Simply controlling the forward speed becomes a much more involved issue than in wheeled vehicles.

A number of legged robots with one, two, three, six, or more legs have been developed up to date, [1-8]. Significant efforts have focused to quadruped robots due to their efficiency compared to complexity, particularly in uneven terrains. Successful implementations in terms of control, design and achieved gaits have been presented. To name a few approaches, a form of PD control has been used to achieve stable running in [3]. A delayed feedback control has been applied to stabilize a bounding gait, though the speed could not directly set, [8]. Further, a number of quadruped designs have been realized, with very different physical parameters, i.e. body mass, leg length, etc., such as the Scout [7], the BigDog [4], the Tekken [5], and the KOLT [6]. The KOLT uses a fuzzy controller to set the speed of a gallop, while Tekken employs a controller based on the Central Pattern Generator (CPG) that alters its active phase based on sensory feedback, [5]. As far as actuation is concerned, Tekken and BigDog robots, both use three actuators on each robot leg. To tackle the problem of actuator weight and design complexity, the Scout robot couples minimal actuation with a suitable designed mechanical system featuring compliant legs and simple control laws that excite the natural dynamics of the mechanical system. However, a time-consuming trial and error determination of controller parameters is required.

An important characteristic of the robots capable of locomotion on uneven terrain is the number of actuators used per leg, as this affects not only the robot weight, but also the complexity of the design, the robot cost and the power autonomy of the system. It is therefore desirable to be able to develop a legged system that can transverse rough terrain and control its forward speed, using as few actuators as possible. On the other hand, the control problem becomes more complex this way, and though it may be possible to produce a stable gait, it is difficult to control both the forward speed and the height of the gait. Another important characteristic of legged robots is the ability of the robot to change its motion characteristics, i.e. to choose the appropriate gait, for example as a function of the terrain it transverses. Keeping controller parameters constant is obviously a significant advantage compared to trial and error designs and lookup table usage. The analysis of robot's dynamics is important for both characteristics and allows for the development of appropriate control laws and mechanical design guidelines. We seek to increase our understanding of the dynamics of straight-ahead level ground running, and hence increase our ability to develop fast and stable legged robots that will be able to follow simple commands.

This paper presents a pronking/ bounding controller for the NTUA quadruped robot, see Fig. 1, and associated experimental results. The controller is based on our previous work [9], and achieves given forward velocity and apex height in a system with only one actuator per leg. Also, the pitching motion, often presented in quadruped running, is kept to a minimum. The control is designed employing the robot dynamics. Moreover, the robot's mechanical sizing and design is based on our previous analysis to provide self-stabilizing characteristics against external perturbations, such as leg-ground interactions and motor control [10]. This analysis results in dynamically stable running with bounding and pronking gaits, with physically realistic and practically achievable forward speeds, apex heights and pitch rates. It is shown through sensor data and high-speed camera captions that the quadruped robot performs pronking and bounding gaits with the desired characteristics.

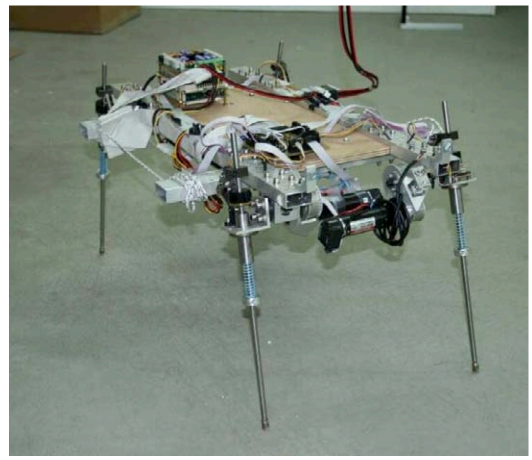


FIGURE 1. THE NTUA QUADRUPED ROBOT. EACH LEG HAS ONE ACTUATOR AND A SPRING.

QUADRUPED ROBOT MODEL

A lumped parameter simple model of a quadruped robot has been developed as an initial controller testbed. This model consists of four compliant legs and a main body. In more detail, each leg has 2 DOFs, i.e. the actuated hip joint and the unactuated prismatic joint with a linear spring, used for energy storage and efficiency. The rotational hip joint allows positioning of legs at desired angles in the plane of the forward motion while the prismatic one allows changes of the legs' length and energy accumulation during the robot's motion.

The dimensionless inertia of the robot body, a quantity with significant role in gait's stability [11], defined as:

$$J = I / (md)^2 \tag{1}$$

is chosen to be 1 as this choice provides a wide range of stable pronking gaits when compared with cases for which the dimensionless inertia is less than one, [11]. As was shown in [12], the selected value has advantages in pitch motion control, also. A specific value of dimensionless inertia can be attained by proper hip placement or redistribution of the body mass.

Planar Model Dynamics

The robot is studied in the plane of its forward motion, performing two types of gaits: pronking and bounding, see Fig. 2. Pronking is the type of gait in which all legs are in the same phase, either in contact with the ground (double stance) or not (flight). The bounding gait has two additional intermediate phases, (shown in light color in Fig. 2), namely the ones in which only one set of legs (front or back) are in contact with the ground. In pronking, zero pitching is expected. However, in the non-ideal case, where body pitching occurs, the back or front legs may strike the ground first. Then, pronking reduces to a bounding gait. The use of a planar dynamics model is valid for pronking and bounding due to their symmetry about the plane of the forward motion. If the vertical motion in the plane of forward motion is also considered, this approach is also valid for trotting gaits [9].

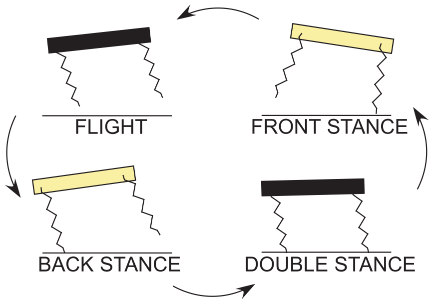


FIGURE 2. GAIT PHASES IN THE PLANE.

As shown in Fig. 3, the body has its center of mass (CoM) at its geometrical center. Each leg is of total mass m_l, inertia I_l, and is actuated by torque τ_j at each hip, where j indicates back (b) or front (f) leg. Each model leg has twice the mass, inertia and spring stiffness of coefficient k of a robot leg and includes viscous friction in the prismatic joint, of viscous coefficient b.

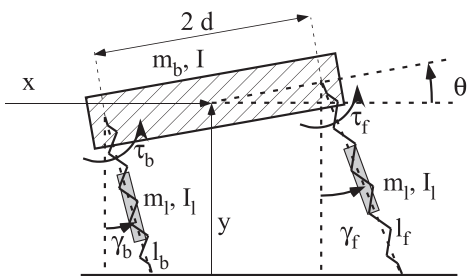


FIGURE 3. PLANAR MODEL.

The robot dynamics are derived using a Lagrangian approach, for the double stance phase of an ideal pronking gait. The main body Cartesian coordinates, x, y, and pitch angle θ, are used as the model's generalized variables. The result is given below:

$$\begin{aligned} &m_b\ddot{x}+k(L-l_b)\sin\gamma_b-b\cdot\dot{l}_b\sin\gamma_b+\tau_b\cos\gamma_b/l_b \\ &+k(L-l_f)\sin\gamma_f-b\cdot\dot{l}_f\sin\gamma_f+\tau_f\cos\gamma_f/l_f=0 \end{aligned} \tag{2}$$

$$\begin{aligned} &m_b\ddot{y}+mg-k(L-l_b)\cos\gamma_b+b\cdot\dot{l}_b\cos\gamma_b+\tau_b\sin\gamma_b/l_b \\ &-k(L-l_f)\cos\gamma_f+b\cdot\dot{l}_f\cos\gamma_f+\tau_f\sin\gamma_f/l_f=0 \end{aligned} \tag{3}$$

$$\begin{aligned} &I_b\ddot{\theta}-bd\cos(\gamma_b-\theta)\dot{l}_b+bd\cos(\gamma_f-\theta)\dot{l}_f \\ &-(d\sin(\gamma_b-\theta)-l_b)\tau_b/l_b+(d\sin(\gamma_f-\theta)+l_f)\tau_f/l_f \\ &+d\cdot k\cos(\gamma_b-\theta)(L-l_b)-d\cdot k\cos(\gamma_f-\theta)(L-l_f)=0 \end{aligned} \tag{4}$$

where leg angles γ_b, γ_f, and lengths l_b, l_f, are substituted for compactness and are given by:

$$\gamma_b=\tan^{-1}(y-d\sin\theta, x_{bt}+d\cos\theta-x) \tag{5}$$

$$\gamma_f=\tan^{-1}(y+d\sin\theta, x_{ft}-d\cos\theta-x) \tag{6}$$

$$l_b=\sqrt{(-x+x_{bt}+d\cos\theta)^2+(y-d\sin\theta)^2} \tag{7}$$

$$l_f=\sqrt{(-x+x_{ft}-d\cos\theta)^2+(y+d\sin\theta)^2} \tag{8}$$

where x_{bt} is the position of the back foot, x_{ft} is the position of the front foot. The double stance dynamics above also yields the dynamics for the remaining stance phases by removing terms that are not pertinent. The leg mass is considered negligible.

During the flight phase, the robot's CoM performs a ballistic motion with constant angular momentum of the system (body and legs) with respect to the CoM:

$$H_o=D_1\dot{\gamma}_b+D_2\dot{\gamma}_f+D_3\dot{\theta}=const. \tag{9}$$

where D_1, D_2, D_3 are given by:

$$\begin{aligned} &D_1=(I_l m^2+l_l^2 m_l m(m-m_l)-l_l^2 m_l^2 m\cos(\gamma_b-\gamma_f) \\ &-dl_l m^2 m_l\sin(\gamma_b-\theta))/m^2 \end{aligned} \tag{10}$$

$$D_2=D_1+(l_l^2 m_l^2 m\cos(\gamma_b-\gamma_f)+dl_l m^2 m_l\sin(\gamma_f-\theta))/m^2 \tag{11}$$

$$D_3=I_b+2d^2 m_l-dl_l m_l\sin(\gamma_b-\theta)+dl_l m_l\sin(\gamma_f-\theta) \tag{12}$$

Assuming that the difference between the leg angles is very small (ideal pronking gait), the angular momentum is written as:

$$H_o=(I+2d^2 m_l)\dot{\theta}+(I_l m^2+l_l^2 m_l m(m-2m_l))(\dot{\gamma}_b-\dot{\gamma}_f)/m^2 \tag{13}$$

The simplified form of (13) has the advantage of being able to predict body pitch following a simple integration.

ROBOT CONTROL

In this section, we present the control algorithm approach, which is based on a novel multipart controller, first presented in [9]. An advantage of this controller is that its gains do not need empirical tuning, but their computation is based on the dynamics of the model, which includes the passive elements also. The controller is designed to reach both the desired forward speed and the desired apex height attained during the flight phase, while the pitching motion is kept to a suitable minimum value during all phases. This is achieved by firstly reaching the desired apex height, and then by controlling the robot's speed, while keeping a minimum pitch change of the whole motion. Also, note that only one actuator per leg is used for the pronking and bounding gaits.

Design

Starting with Eqs. (2)-(4) and assuming that the difference of the leg absolute angles and main body's pitch angle are small as demanded by the ideal pronking gait, writing out the leg lengths as functions of y, θ, γ_b, γ_f and approximating the leg lengths by the leg rest length L for the terms that include torques, the robot's dynamics take a simpler form:

$$m_b\ddot{x}+k(L-y)\sin\gamma_{sum}=-(\tau_b+\tau_f)/L \tag{14}$$

$$m_b\ddot{y}+2b\dot{y}+2ky+mg-k\cdot L(\cos\gamma_b+\cos\gamma_f)=0 \tag{15}$$

$$I_b\ddot{\theta}+2bd^2\dot{\theta}+2d^2k\theta+k\cdot Ld(\cos\gamma_b-\cos\gamma_f)+\tau_b+\tau_f=0 \tag{16}$$

where γ_{sum} is the sum of the leg angles. For a gait of speed $\dot{x}$, and during stance, the evolutions of the leg angles can be taken as [1]:

$$\gamma_j=\gamma_{j,td}-\dot{x}t/L \tag{17}$$

where $j = b, f$, $\gamma_{j,td}$ is the leg touchdown angle, and time t counts from each leg touchdown. Using trigonometry and Eq. (17), the double stance dynamics become:

$$m_b\ddot{x}+k(L-y)\sin\left(\gamma_{sum,td}-\frac{2\dot{x}t}{L}\right)=-\frac{\tau_b+\tau_f}{L} \tag{18}$$

$$m_b\ddot{y}+2(b\dot{y}+ky)=-m_bg+2kL\cos\left(\frac{\gamma_{sum,td}}{2}-\frac{\dot{x}t}{L}\right)\cos\left(\frac{\gamma_{dif,td}}{2}\right) \tag{19}$$

$$\begin{aligned}&I_b\ddot{\theta}+2d^2b\dot{\theta}+2d^2k\theta=\\&2kLd\sin\left(\frac{\gamma_{sum,td}}{2}-\frac{\dot{x}t}{L}\right)\sin\left(\frac{\gamma_{dif,td}}{2}\right)-\tau_b-\tau_f\end{aligned} \tag{20}$$

where $\gamma_{sum,td}$ is the sum of the leg touchdown angles and $\gamma_{dif,td}$ is the difference of the leg touchdown angles. The form of Eqs. (18)-(20) is very important as it points towards using the parameters $\gamma_{sum,td}$, τ_b and τ_f, the hip torques, and $\gamma_{dif,td}$ as control inputs.

Given the initial conditions for y and the assumption that $\gamma_{dif,td}$ is small due to the ideal pronking gait assumption, Eq. (19) can be solved and used to compute $\gamma_{sum,td}$ such that the robot acquires some desired apex height, as:

$$\gamma_{sum,td}=f_1\left(\underbrace{m,k,L,d,I,b,g}_{\text{robot parameters}},\ \underbrace{\dot{x}_{des},h}_{\text{gait parameters}}\right) \tag{21}$$

In Eq. (18), the forward dynamics is coupled with the vertical motion of the robot, due to the influence of the prismatic leg springs on the forward motion of the robot. To compute the applied torque, we use the result of solving the vertical oscillation from Eq. (19), and also the sum of the touchdown angles computed in Eq. (21), as:

$$\tau=f_2\left(\underbrace{m,k,L,d,I,b,g}_{\text{robot parameters}},\ \underbrace{\dot{x}_{des},h}_{\text{gait parameters}},\ \underbrace{\gamma_{sum,td}}_{\text{control parameter}}\right) \tag{22}$$

In Eq. (20), the governing dynamics has again the form of a driven oscillator. The control must keep the pitching motion of the robot to a minimum, so the difference of the leg touchdown angles is computed as:

$$\gamma_{dif,td}=f_3\left(\underbrace{m,k,L,d,I,b,g}_{\text{robot parameters}},\ \underbrace{\dot{x}_{des},h}_{\text{gait parameters}},\ \underbrace{\gamma_{sum,td},\ \tau}_{\text{control parameters}}\right) \tag{23}$$

Note that $\gamma_{dif,td}$ is used to control the pitching motion of the robot only. In this way, the sum of the leg touchdown angles, $\gamma_{sum,td}$, and the hip torques τ_b and τ_f are available for controlling the forward and vertical motions of the robot. This is done by choosing the right values for the applied hip torques in stance and the sum of touchdown angles can be defined to control the robot's forward and vertical motion.

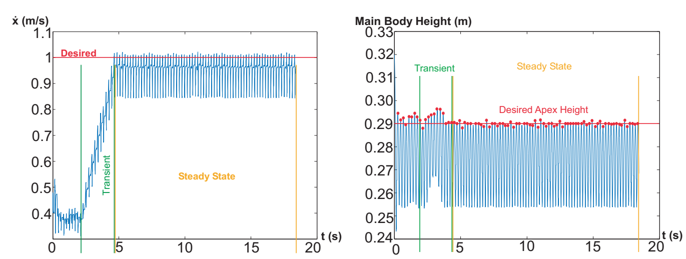
Implementation

At this point, a step-by-step analysis is presented on how the control algorithm is implemented in practice. Sensors on the robot provide leg angle position and velocity, leg length and velocity, and body pitch and pitch velocity. The quantities associated with the legs may be measured with encoders, while an inertial measurement unit provides pitch measurements.

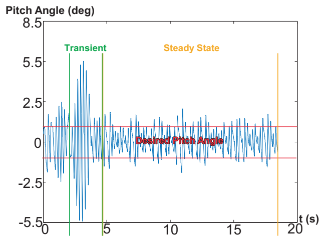
Starting right before the robot leaves the ground and enters into a flight phase, sensor data and robot geometry is used to compute the full state, solving Eqs.(5) - (8) for the robot states using on-board computing. Once the state at liftoff is known, the flight dynamics is relatively simple to integrate using Eq. (13), and so the expected touchdown state can be found. Then, the three functions in Eqs. (21) - (23) are used to compute $\gamma_{sum,td}$, τ_b, τ_f and $\gamma_{dif,td}$ such that at the next apex point, the robot will have the desired forward speed and height, while keeping body pitch angle to a minimum. The hip actuators position the legs at the desired angle for touchdown during flight and also move the legs during the entire stance phase using the calculated torques τ_b and τ_f.

Simulation Results

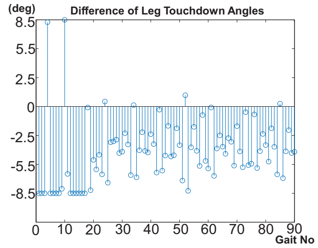
A quadruped robot is simulated for validation of the performance of the control algorithm. The robot is considered to be released 0.05m above the ground with near zero pitch angle, while it has no vertical velocity and forward speed of 0.4 m/s. The motion of the robot body is constrained to the plane of forward motion. The controller drives the robot to a desired forward speed of 1 m/s (Fig. 4 (A)) and desired apex height of 0.29 m (Fig. 4 (B)), while retaining a pitching motion within bounds (Fig. 4 (C)).



(A) (B)



(C)



(D)

FIGURE 4. ROBOT RESPONSE FOR (A) FORWARD SPEED, (B) BODY HEIGHT, (C) PITCH ANGLE, AND (D) $\gamma_{dif,td}$.

QUADRUPED ROBOT MECHATRONIC DESIGN

The NTUA Quadruped Robot has four legs with springs, and with one actuator per leg. The total mass of the robot is 11 kg, including motors, gearboxes, sensors, electronics, batteries and onboard computer. The rest of the robot physical parameters are presented in Table 1.

TABLE 1. NTUA QUADRUPED ROBOT PHYSICAL PARAMETERS

Parameter	Symbol	Value	Units
Robot mass	m	11.00	kg
Leg rest length	l_o	0.33	M
Spring stiffness	k	3.349 x10^3	N/m
Hip joint distance	$2d$	0.54	m
Body inertia	j	2.917	kg.m^2

All robot parameters in Table 1 have been selected following a systematic methodology and are optimal according to the set criteria. Specifically, the *shape* of the quadruped robot, i.e., the relation between its physical parameters, and its *size*, i.e., the physical magnitude of it, have been determined through an optimization scheme that included commercially available motor and gearbox data. The desired performance criteria were: (a) minimization of the actuator effort to sustain a certain motion, very close to a passive one, and (b) maximization of payload capability of the robot, for the target robot mass, [10].

Mechanical Design

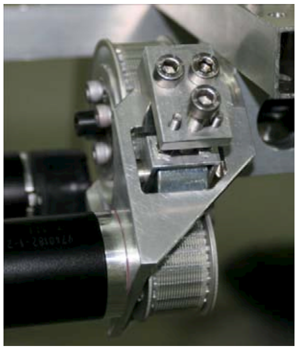
The design of the NTUA's quadruped robot emphasizes simplicity and is parametric and modular. Simplicity is important for reliability, good knowledge of system parameters and reduced maintenance cost. The parametric design is desired for quick and simple adjustments of the basic geometric and mass properties. Due to modularity, the robot's mechanical parts can be replaced easily in case of failure during experiments.

Frame. The chassis of the robot is made of aluminum and is modular, see Fig. 5(A). The basic physical parameters that can be adjusted include the body's length, the body's width, and the total weight distribution/ symmetry. This can be accomplished by positioning the elements that constitute the frame in different places using a number of pre-drilled holes on them.

Legs. Each leg consists of two parts. The lower part slides into the upper part to form a prismatic joint. A spring coil connects the two, to form a springy leg. The leg's length at spring rest can be adjusted to a maximum of about 25% of the average leg length. Due to the required durability against impact forces, the legs are made of steel while their toes are covered by an element made from shock absorbing material, Fig. 5(B). To avoid toe slippage, this material also keeps the friction between the ground and the leg toes high.

(A)

(B)



(C)

(D)

FIGURE 5. ROBOT'S CHASSIS AND DETAILS. (A) ROBOT FRAME, (B) SPRINGY LEG, (C) HIP JOINT AND MOTOR, AND (D) LEG LENGTH MEASUREMENT MECHANISM.

Actuators. As a result of the system optimization procedure, four Maxon RE30 60W DC motors were selected, each delivering 0.85 Nm maximum continuous output torque. The torque is transferred to the leg through a gearbox and a pulley-belt mechanism, shown in Fig. 5(C). The torque finally delivered to each leg is 6.5 Nm corresponding to a total transmission ratio of

76.5:1. The angular position for the hip joint is acquired using a full quadrature 500 cpr encoder fitted on the motor.

Passive Joint. Besides the motor actuated joint, there is a passive compliant linear joint with a spring, used for storing and re-supplying energy between the different phases of a gait. The linear position of the leg (spring compression) is acquired using a knee-type mechanism, which transforms the linear leg's displacement to an angle counted by a full quadrature encoder (360cpr resolution). This feedback mechanism is shown in Fig. 5(D). The design of the passive joint allows the spring pre-tension to be adjusted. Also, the spring can be easily removed and replaced with other springs of different stiffness or even length. The adjustment capability of the leg's stiffness and maximum spring compression is very useful during experiments.

Control Electronics

The central control unit is a PC/104 with a 256MB RAM 650MHz Celeron embedded computer. The operating system is a real-time patched Arch Linux distribution with kernel 2.6 using RTAI. Its functions are to collect sensor data, implement the control algorithm and compute the desired output torque for each motor and each leg's touchdown angle. The control loop time is 1 ms (1 kHz) which is fast enough for this application. The computation of these values is based on feedback acquired from embedded sensors. As mentioned, the angles and linear displacement of the legs are given by encoders. The pitch angle and angular velocity of the robot are acquired by a high-speed Analog Devices ADIS 16354 6DOF inertial measurement unit (IMU). In order for the feedback from the sensors to be read, processed and transmitted to the PC104, a custom PCB was developed, see Fig. 6. This PCB has 8 dsPIC microprocessors that read encoder data and software-enhance the output resolution from 500 cpr to 2000 cpr and 360 cpr to 1440 cpr for the hip angle and linear displacement respectively. Angular velocities of the hip joints and the linear velocity of the spring joints are also calculated onboard using the dsPICs software timers. A primary AVR microprocessor is used for communication with the dsPICs and the IMU. This primary AVR is connected to a secondary AVR, enabling the faultless communication between the PC104 and the primary AVR, using a custom communication protocol.

Following the calculation of torques and angles, the data is sent back to the PCB, which converts them from digital to analog using pulse-width-modulation (PWM), in order to send commands to the motor drives. The motor drives are the DZRALTE-012L080 from Advance Motion Control (AMC), and were chosen for their compact size and ability to supply each motor with 6A continuous, 12A intermittent current. The whole robot is supplied with power by packs of Li-Po batteries or by two Siemens SITOP 24V power supplies, one 5 A and one 25 A. The 5 A is used for powering the electronics and the PC104 and the 25 A one is used for supplying the motors. Batteries are used when necessary (e.g. final or outdoor experiments), otherwise external power in more convenient to use.

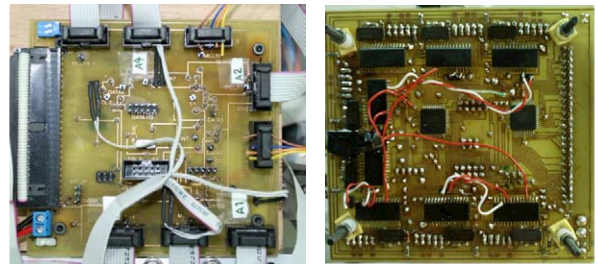


FIGURE 6. CUSTOM PCB FOR READING SENSORS.

EXPERIMENTS

The multipart controller is applied to the robot for achieving bounding and pronking gaits. In each experiment, the robot is released from a height of approximately 0.05 m above ground. This way of starting is necessary for achieving an initial spring compression. The robot continues its periodical motion through the separate phases that characterize each gait. The experiments were carried out on a flat surface. The basic goals of these initial experiments are to test the successful realization of the prototype and its gait behavior when the multipart controller is applied.

The controller is commanded to guide the robot in achieving gaits with desired forward speed $\dot{x} = 1.0$ m/s, apex height $h = 0.29$ m and body pitch velocity $\dot{\theta} = 0$ deg/s. Next, we present initial results of the robot performing bounding and pronking gaits. By studying the capture images aquired by a high speed camera (500Hz) it can be verified that the above values tend to be achieved. Data from the robot's IMU also confirms this.

Results

Bounding Gait. The bounding controller was set up first. The target height was set to 0.29 m and the target speed was set at 1.0 m/s, while keeping pitch angle to a minimum. The experiment was captured by a high-speed camera running at 500 Hz, and the sensor data was logged. A careful study of the captured frames and the processed data shows that bounding was successfully performed and the desired values for the speed, height and minimum pitch angle tend to be met. More specifically, Fig. 7 presents a full bounding gait in which the robot goes through all the described phases. It is clear that the robot in the first and last captured frame is in the exact same phase and that it has covered a full bounding gait in-between. This bounding gait is also confirmed by studying Fig. 8 (especially Fig. 8 (B)), which shows that the front legs are not in sync with the rear legs.

As mentioned earlier, the control algorithm's primary target is to achieve the desired apex height value. By extracting the frames in which the robot reaches the apex height, it is shown that the desired apex height is maintained and sustained, see Fig. 9. Figure 10 shows the small deviation of the actual apex height from the desired apex height. After having the desired height, the algorithm tries to meet the desired velocity value. Figure 11 shows how the average speed of each gait is calculated, i.e. as the distance covered in a specific time. The time is calculated as the difference between two adjacent snapshot timestamps and the distance covered is measured by studying the forward movement of a characteristic part of the robot.

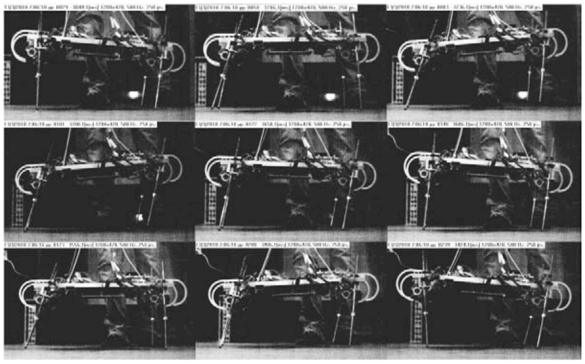
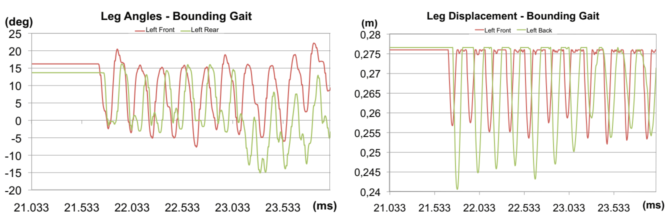


FIGURE 7. REALIZATION OF A BOUNDING GAIT.



(A) (B)

FIGURE 8. COMPARISON BETWEEN FRONT AND REAR LEGS IN TERMS OF (A) ANGLES AND (B) SPRING DISPLACEMENT.

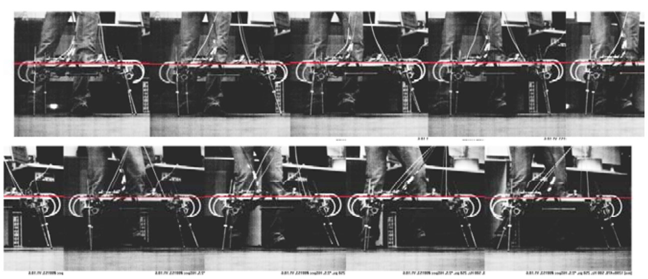


FIGURE 9. VERTICAL DISPLACEMENT OF ROBOT'S CENTER OF MASS DURING BOUNDING GAIT.

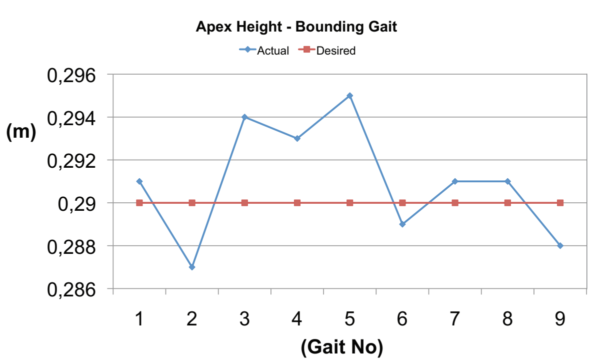


FIGURE 10. BOUNDING ACTUAL & DESIRED APEX HEIGHT.

In Fig. 11, we have selected a part of the chassis as a reference point and marked its position for all gaits with a thin red line. We then see what part of the robot has this line moved to in the next frame and we measure the actual distance between these two robot parts on the robot. This way we estimate the distance covered between the two frames. We have used the calculated data for the forward velocity to plot Fig. 12. By studying Fig. 12, we see that the robot's speed is constantly increasing towards the desired value. Due to space restrictions it was impossible to keep the robot's motion for longer, but it is clear that the desired speed value tends to be reached.

By plotting the processed IMU data, we can see that the pitch angle tends to zero, see Fig 13. As the IMU output is the Y-gyro value (pitch angle velocity), we use integration to extract the pitch angle. This results in a drift of the pitch angle. It is obvious though that the pitch angle deviation is reduced with each gait.

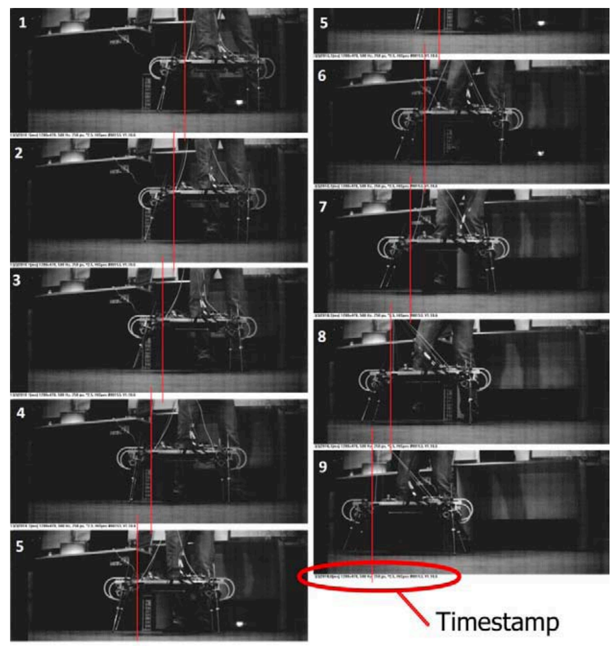


FIGURE 11. COVERED DISTANCE IN 9 BOUNDING GAITS.

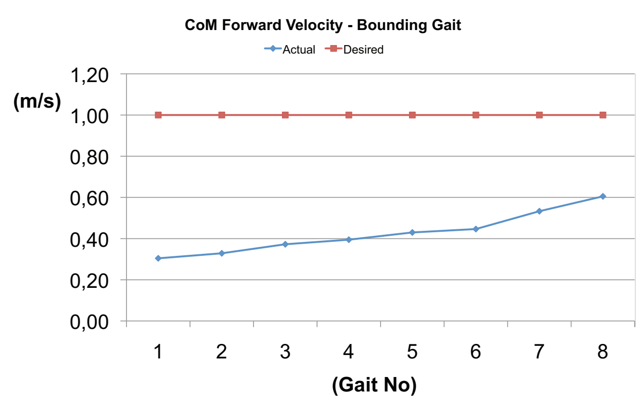


FIGURE 12. FORWARD VELOCITY OF ROBOT'S CENTER OF MASS DURING BOUNDING GAIT.

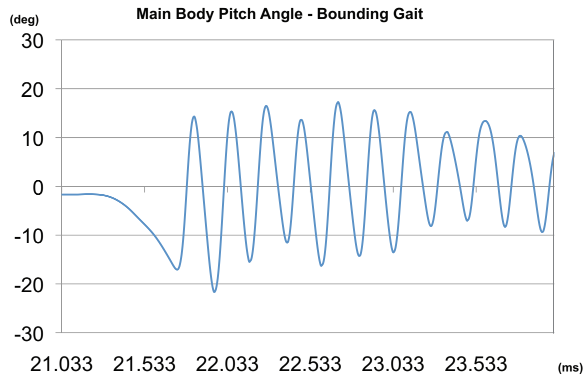


FIGURE 13. PITCH ANGLE DURING BOUNDING MOTION.

Pronking Gait. During experiments for the realization of a pronking gait, the robot's body maintains an almost zero pitch velocity during all phases, see Fig. 14. This demonstrates that the robot can achieve pronking, both due to its design and its controller. As shown in Fig. 14, the four legs are in phase and well synchronized. Quantitative results on pronking will become available soon.

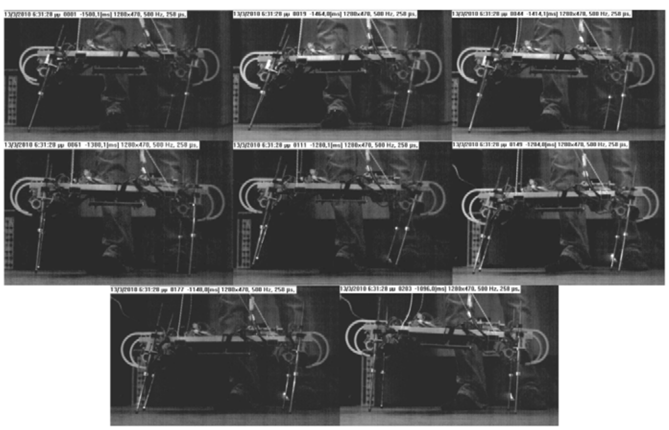


FIGURE 14. REALIZATION OF PRONKING GAIT

CONCLUSIONS

This paper presented a multipart pronking/ bounding controller for a quadruped robot and corresponding experimental results. The robot achieved given apex height and forward velocity with only one actuator per leg. The quadruped was designed based on an optimization methodology and was built allowing for changes in its geometry and parameters. Experimental results were obtained using internal sensors and high-speed camera captions.

It was shown that the quadruped robot is capable of dynamic motion. Also, it was able to successfully accomplish initial full bounding gaits, after which it was stopped due to space restrictions. First results for pronking type gaits are also promising. Further improvements and experiments will follow, aiming towards a more stable and faster movement.

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