

Implementation and experimental validation of an autonomous hexapod robot

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Abstract—This paper describes the implementation of a bio-inspired six legged robot: Gregor I. Both structure and locomotion control are inspired by biological observations in cockroaches. Robot mechanics attempts to emulate main structural features in cockroaches, like self-stabilizing posture and specializing legged function; in turn, locomotion control is based on the theory of the Central Pattern Generator. The final aim is to artificially replicate the fundamental principles that guarantee cockroach’s extraordinary agility. Our major concern was on the implementation of rear legs, that seem to play a crucial role in obstacle overcoming and payload capability, and on the locomotion control, performed in this work by a Cellular Neural Network playing the role of an artificial Central Pattern Generator. Experimental tests showed that Gregor I is able to walk at the travel speed of 0.1 body length per second and to successfully negotiate obstacles more than 170% of the height of its mass center.

I. INTRODUCTION

The concept of a mission capable legged robot is acquiring an ever increasing interest in the field of explorative robotics. On one hand legged robots would possess clear advantages over wheeled robots like obstacle climbing capability and mechanical graceful degradation, on the other hand their development has been hampered by the challenging task of actually implementing an efficient structure and designing an effective locomotion control.

Strongly believing that a bio-inspired approach can largely benefit the design of an autonomous legged robot, we took explicitly inspiration from cockroach experimental observations.

In order to replicate at least in part cockroach extraordinary agility, each of the three leg pairs has a unique design: front legs and middle legs, different in dimensions, have 3 degrees of freedom and a kind of pantograph dynamics aimed at facilitating obstacle climbing task, while rear legs have 2 degrees of freedom and a piston-like design suitable for powerful forward thrusting. Our main concern is on the mechanics of rear legs, that seem to play a crucial role in obstacle overcoming and payload capability. Moreover Gregor I exhibits a *sprawled posture*, able to guarantee a statically stable posture and thus a high margin of stability [1].

For locomotion control, we took inspiration from the biological paradigm of Central Pattern Generator (CPG) [2]. In insects, the activation of the appropriate muscles in the legs and their coordination take place locally by means of

groups of neurons functionally organized in CPG modules. In our work, basic units of the adopted artificial CPG are nonlinear oscillators coupled together to form a network able to generate a pattern of synchronization that is used to coordinate robot actuators. Cellular Nonlinear Network (CNN) paradigm, introduced in [3], provides a framework for the implementation of these nonlinear oscillators: each oscillator is simply viewed as a cell of a CNN. This technique has been previously used to control the locomotion of several different bio-inspired robotic structures: simple hexapods, octopods and lamprey-like robots [4], [5]; here this technique is extended to the control of an hexapod in which each leg pair has a unique design. A direct VLSI realization of the control system is possible: a chip for locomotion control implemented by a CNN-based CPG is introduced in [6].

This approach, thanks to its intrinsic modularity, allows an arbitrarily large number of actuators to be controlled concurrently and thus is particularly suitable for legged locomotion control. Further advantages are ease of implementation, robustness, flexibility.

During the design phase, computer-aided design allowed to properly select dimensions, weights and articulation angles of each leg limb, to tune the position of the center of mass, to evaluate motor torques and to test the locomotion control. Simulation results led to the implementation of the first prototype.

All the details concerning the design phase are reported in [7]; in this paper, instead, we describe the implementation of Gregor I, discussing both the mechanics and the hardware control architecture. Moreover, we report the performed experimental tests.

Results are encouraging, since the robot Gregor I is able to walk at the travel speed of 0.1 body length per second and to successfully negotiate obstacles more than 170% of the height of its mass center.

II. ROBOT DESIGN AND LOCOMOTION CONTROL

The design of Gregor I and its biological inspiration are described in detail in [7]. Here, for sake of clarity, we quickly overview the main features.

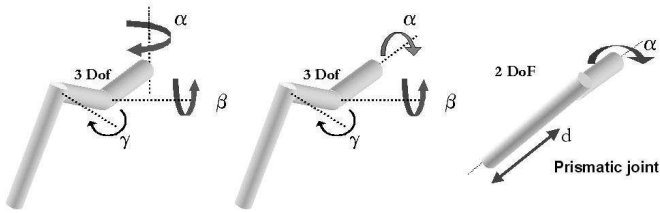


Fig. 1. Front Leg (left), Middle Leg (center) and Rear Leg (right).

A. Design

Each leg pair has a unique design. Front legs have to provide enough flexibility to guarantee efficient obstacle approach and effective postural control; therefore, front legs are divided into three segments (analogous to coxa, femur and tibia), articulated through 3 rotational joints (α , β and γ joints in Fig. 1).

Basically, middle leg design is identical to front leg design as far as number of segments and joint types are concerned; nevertheless, middle legs have to provide part of the forward thrust; toward this end, the α axis is modified as shown in Fig. 1.

Both in front legs and in middle legs, joint α allows leg forward movement, joint β allows raising movement and, finally, joint γ guarantees roll and pitch angle control. The γ joint plays a fundamental role in the attitude control, but is not needed for basic locomotion; therefore in this work, since we are firstly interested in basic locomotion, γ joint is kept at a constant value (0.5 rad from the vertical). Overall, the dynamics of front and middle legs closely resembles the dynamics of a pantograph mechanism.

Rear legs are divided into two segments (coxa and tibia respectively); since main function of rear legs is powerful thrust, we considered a robust and compact design suitable for “bang-bang” pneumatic actuation. Coxa segment is articulated with the body through a rotational joint (α joint), while the coxa-tibia joint is prismatic (d joint), as shown in Fig. 1; α joint provides forward movement, while the d joint provides raising movement. Thus, rear legs possess a peculiar hybrid linear/rotational actuation that could allow the use of a combination of electrical and pneumatic actuators.

In order to confer a sprawled posture with a pitch angle of $\varphi \simeq 20^\circ$, legs articulate differently with the body; overall, robot length is 30 cm and robot CoM height is 5 cm.

B. Locomotion control

Gregor I locomotion control is based on the theory of Central Pattern Generator. Gregor I CPG is made of six two-layers CNN cells, each one controlling through its two outputs y_{CPG}^2 and y_{CPG}^1 a leg (respectively: the α and β joints in front and middle legs and α and d joints in rear legs). The dynamics of each cell is characterized by a limit cycle, that is mapped into a leg limit cycle [8].

The CNN outputs do not directly control the actuators; they instead undergo a transformation in order to fit the peculiar leg kinematics.

Synchronization is achieved through suitable connections among the cells depending on the adopted gait, as discussed in [8]. In particular we considered connections able to guarantee a fast gait.

III. GREGOR I STRUCTURE

In this section, we describe the mechanical structure of Gregor I.

A. Body

The main body, parallelepiped in shape, is 30 cm long, 9 cm wide and 4 cm high; the body is simply made of two aluminium sections joined by two threaded bars. This simple structure makes room for onboard electronics and batteries, and just weighs 200 g.

B. Legs

As described in the previous section, front legs are divided into three segments. All segments are simply made of aluminium sections, whose lengths are reported in Tab. I.

TABLE I
COXA, FEMUR AND TIBIA LENGTHS IN FRONT LEGS

Segment	Length <i>cm</i>
Coxa	6.5
Femur	4.5
Tibia	8.7

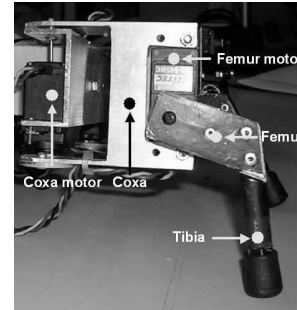


Fig. 2. Front Leg.

For simplicity, middle legs are equal to front legs except for the length of the tibia segment that, in order to confer a sprawled posture, is a bit shorter: 7 cm.

Rear legs are actuated by two servomotors, the former aimed to control the rotational joint α , the latter employed to realize the prismatic movement (protraction/retraction - joint d) of a cylindrical bar. To convert the rotational energy from the motor to linear oscillations, a transmission mechanism based on a crank-slider has been adopted. Moreover, to avoid the overloading of the motor axis used to control the α joint, a support axis has been realized; the support axis sustains the plate with the second motor and the cylindrical bar, and is connected with a transmission mechanism to the α motor.

Fig. 3 shows from a side view the two phases of rear leg movement: during the swing phase the leg is raised up with a

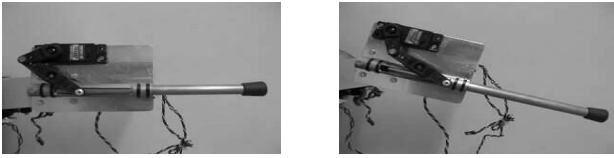


Fig. 3. Rear leg movement.

counter-clock rotation of the α joint and the cylindrical bar is retracted; during the successive stance phase the leg points to the ground and the cylindrical bar is pushed until a complete extension is obtained.

Similarly, all segments are simply made of hollow aluminum tubes, whose physical dimensions (radius and height respectively) are reported in Tab. II.

TABLE II
COXA AND TIBIA DIMENSIONS IN REAR LEGS

Segment	Dimensions <i>cm</i>
Coxa	0.5×5
Tibia	0.5×15

The range of motion of each DOF is just as important as the number of DOF in the legs and their basic dynamics. The ranges of motion are summarized in Tab. III. The 12 active

TABLE III
DESIRED RANGE OF MOTION

Front legs	Coxa (degrees)	Femur (degrees)
	60	60
Middle legs	Coxa (degrees)	Femur (degrees)
	60	60
Rear legs	Coxa (degrees)	Tibia (cm)
	15	2

joints in the legs are actuated by 12 servos Hitec HS-945MG delivering a stall torque of 11 Kgf · cm and weighing 50 g.

C. Overall structure

Fully assembled Gregor I weighs 1.2 kg; with respect to the bottom of the body, front part is 7 cm high and rear part is 1 cm high. CoM is 5 cm high and the pitch angle is 20 degrees as desired; thus, Gregor I, shown in Fig. 4, exhibits a sprawled posture.

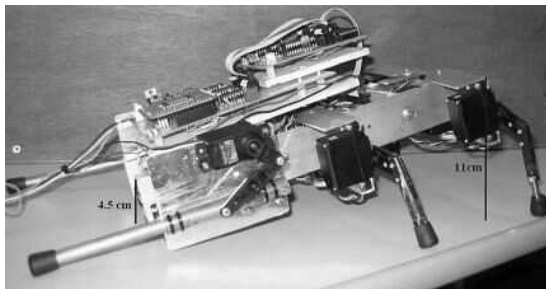


Fig. 4. Gregor I.

IV. CONTROL ARCHITECTURE

The core of the control architecture is the CNN-CPG chip described in [6]. The overall control architecture is shown in Fig. 5.

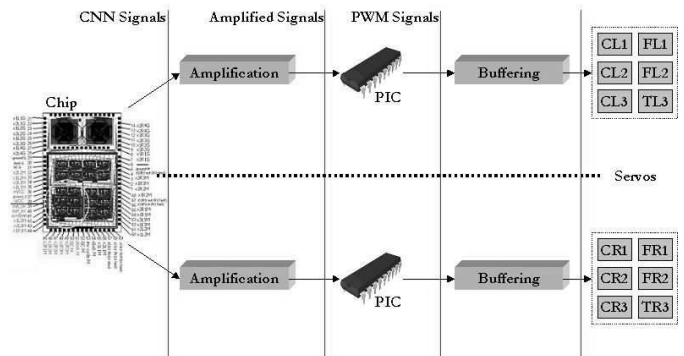


Fig. 5. Control architecture.

For the present, power supply is external. Control architecture is supplied at ± 8 V; this voltage is then stabilized at ± 5 V. The core of the architecture, *i.e.* the CNN-CPG chip, generates the twelve basic signals needed for locomotion (Fig. 6), as discussed in Section II. In particular, we selected through the chip input Gait Control the Fast Gait Mode in order to obtain a fast gait; moreover through the chip input Clock we provided a clock signal at 50 Hz that guarantees a locomotion step with frequency 0.5 Hz. CNN-CPG signals have an excursion from -2.5 V to 2.5 V.

Servos need PWM signals for the control, therefore CNN-CPG outputs have to be converted in PWM signals. Toward this end, CNN-CPG outputs firstly undergo an amplification stage made of TL914 operational amplifiers; after this stage, signals are in the range 0 – 5 V. Then, signals are converted through PIC 18F2320 in PWM signals (each PIC converts 6 signals). Conversion is such that the desired ranges of motion are achieved (see Tab. III). Finally, PWM signals undergo a decoupling stage.

V. EXPERIMENTAL TESTS

In the sequel, we will document the robot's speed, its maneuverability, obstacle climbing capability, and energetic performance. Most of the results are in accordance with the simulation results provided in [7]. Videos are available at the URL [9].

A. Forward locomotion

Speed has been measured simply relying on a chronometer and a rule and considering, as stated above, a fast gait and a

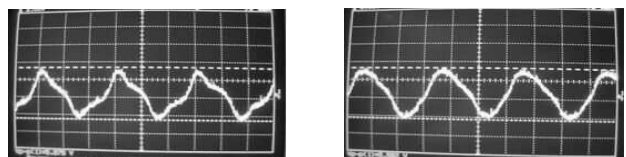


Fig. 6. CNN-CPG signals for front leg (coxa and femur respectively).

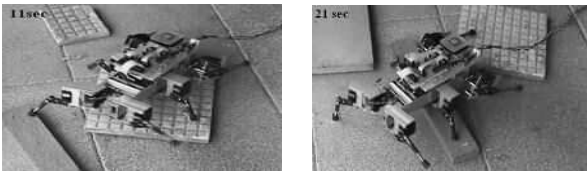


Fig. 7. Obstacle course.

step frequency of 0.5 Hz. Gregor I travels at the acceptable speed of 0.1 body length per second.

B. Turning

As predicted by our simulations, steering is possible, via differential motion between left and right legs; differential motion is achieved by setting at 0 V in the CNN-CPG chip the inputs *Out_sx* for left turning or *Out_dx* for right turning.

C. Obstacle course

To demonstrate Gregor I rough terrain capabilities, we constructed an obstacle course made of 7 randomly spaced obstacles between 2 and 4 cm high (that is, between 23 % and 46 % of front leg length and exceeding ground clearance between 1 and 3 cm). Over 10 runs, 9 runs were successful, while in one run Gregor I broke one leg.

D. Obstacle climbing

The obstacle climbing capabilities of Gregor I were evaluated with two different obstacles. Firstly an obstacle 8.5 cm high, *i.e.* 170 % of robot CoM height or 121% of front part height, was considered: over several trials the robot was always able to surmount it. Then, we tested Gregor I over a composite obstacle with a maximum height of 12.5 cm; obstacle was overcome successfully. It is worthwhile to notice in Fig. 8 the powerful forward thrust provided by rear legs.

As a comparison, RHex [10] is able to negotiate obstacles with height 130% of front part height, while Sprawlita [11] is able to negotiate obstacles with height 100% of front part height. Therefore Gregor I exhibits excellent obstacle climbing capabilities.

E. Energetic performance

Power consumption ranges between 15 W during walking on even terrain and 25 W during obstacle course.

To measure energy efficiency we use the “Specific Resistance” ϵ [12]:

$$\epsilon = P/(mgv)$$

based on the robot’s weight, mg , and its average power consumption, P , at a particular speed, v . Specific Resistance is increasingly popular and can be used to compare vehicles regardless of size, speed or configuration.

The specific resistance was lowest on even terrain, $\epsilon = 42$, and highest during obstacle course, $\epsilon = 70$. As a comparison, RHex robots Specific Resistance ranges between $\epsilon = 2.5$ and $\epsilon = 14$ [10]. Therefore energy efficiency of Gregor I is, for now, very low and needs to be improved. We believe that we could significantly increase energetic efficiency by redesigning coxa joint of rear legs.

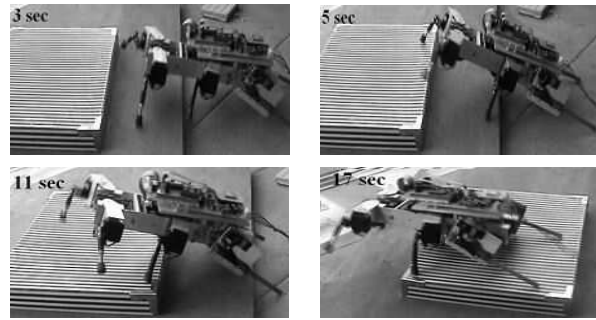


Fig. 8. Climbing of a composite obstacle 12.5 cm high.

VI. CONCLUSIONS

We have built an experimental platform to test the design concepts for an innovative hexapod robot.

Experiments with the robot are encouraging: Gregor I, thanks to its sprawled posture and innovative piston-like actuation for rear legs, is able to negotiate high obstacles. On the other hand, energetic efficiency should be improved significantly.

Moreover, the CNN-CPG approach has been shown to be suitable also for the locomotion control of legged robots equipped with legs with a complex design.

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