Controller for a four legged walking machine

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Abstract

In this paper we describe a controller for 4-legged robot locomotion implemented on a 4-legged walking machine. This controller uses a ring of coupled nonlinear oscillators. It is very efficient, needing no software and only a small number of components to guarantee coordination between the leg movements leading to walking. We explain how inter-leg coordination is achieved and we show data which confirms that, depending on the state of the controller, two different gaits can be observed in the resulting behaviour of the robot.

1 Introduction

Coupled oscillators used to control locomotion have been the topic of a rather long history of research. In lamprey locomotion central pattern generators (CPGs), based on neurons acting as coupled oscillators, are believed to be the cause of inter-segmental coordination[1]. Insect walking offers more controversy on the subject of the controller. While the model introduced by Pearson [2] is a CPG, Cruse et al. believe in a purely reflex-based model [3]. These two models are extreme views, leaving room for different hybrid controllers, both for implementation as well as for modelling. In hybrid controllers the basic rhythm is generated by a network of oscillators, but can be modified by sensory information. Ferrell[4] has compared the performance of different kinds of controllers employed to generate 6 legged walking on a robot. A hybrid model seemed to show the most robust performance. The controller presented here falls into the category of hybrid controllers. It can generate stable walking without sensory input, but allows the robot's behaviour, for example its direction of motion or its gait, to change in accordance with sensory information. This paper discusses an investigation of inter-leg coordination control.

2 The mechanical machine

The robot consists of a flat, rectangular, 9cm x 3cm body, parallel to the ground, with 2 DC motors attached, as sketched in Figure 1 . Each motor drives a pair of legs, shaped in a U-form with additional angles in the plane of the body. The front legs are driven by a motor with its axis perpendicular to the body and they can therefore move backwards and forwards, while the hind legs are actuated by a motor with its axis is parallel to the body. As the hind motor turns, the legs attached to it stay on the ground so that the body rolls from side to side. This results in changing the weight distribution on the front legs.

3 The controller

The idea for this controller was introduced by Tilden [5]. It fits within his framework of rings of coupled differentiators[6,7,8,9]. The controller implemented here is simpler than the original controller, but uses the main element which is a ring of coupled oscillators. The controller consists of four elements of the kind shown in Figure 2, coupled together in a ring, as shown in Figure 3. Each of these elements gives a 'signal' output (which is a drop in voltage from 5V to 0V at time $t = t_1$, followed by a step back to 5V after a time T) as a result of an edge (abrupt rise from 0V to 5V) occurring at its input node Vin at time $t = t_1$ (see Figure2). The signal duration time can be calculated by solving the differential equation for the voltage V at the input node of the inverter:

$$\dot{V} + \frac{V}{\tau} = \dot{V}_{in}$$

(where $\tau = RC$ is the time constant of the high pass filter).

The solution

$$V = V_{max} e^{-\frac{t}{\tau}}$$

(with V_{max} = maximal voltage at node V)
leads to the time it takes V to relax back to the threshold of the inverter. This can be identified with the signal duration time T:

$$T = RC \ln \frac{V_{max}}{V_{th}}$$

(with V_{th} = (high to low going input) threshold voltage of the inverter).
Note that this duration is proportional to the time constant $\tau = RC$ (V_{max} and V_{th} can be assumed to be constants). Since the capacitances C are kept constant and identical in the controller described here, the resistances are the parameters that control the signal duration time in each of the elements used in the controller.

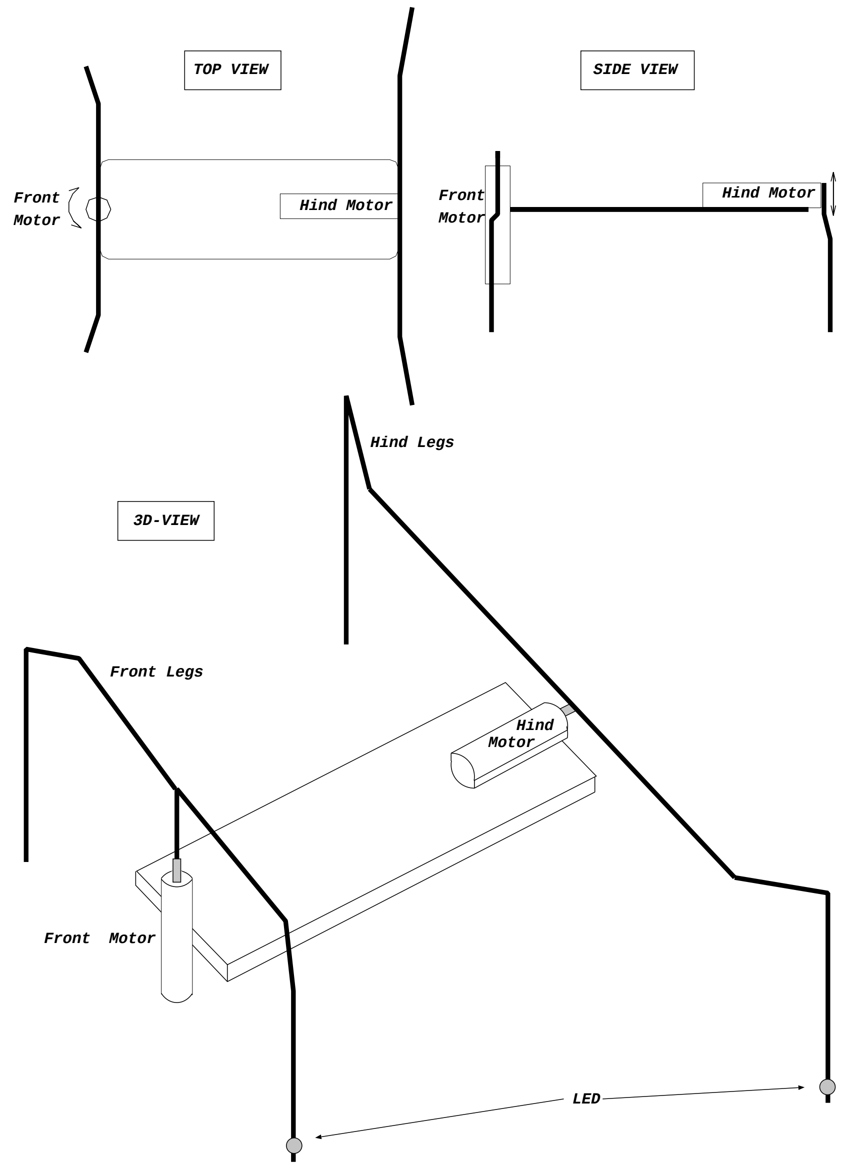

Figure 1: Schematic of the robot. The upper drawings show a top and a side view, the lower one is a three dimensional sketch of the machine.

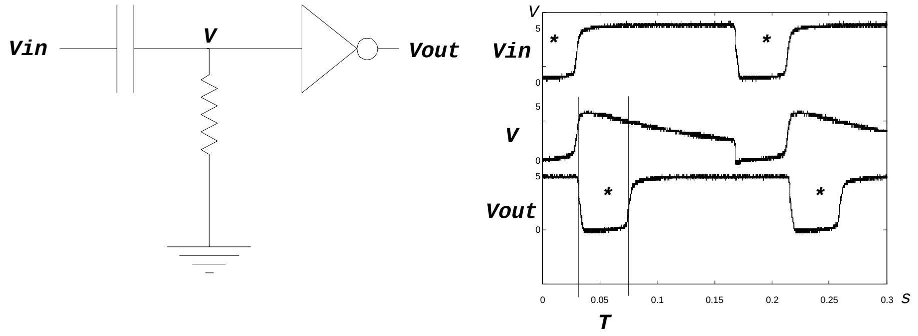

Figure 2: The basic element used in the controller is composed of a high pass filter and a TTL inverter. The voltages measured show how a rise in voltage Vin results in a rise in V, which then decays proportional to $e^{-t/\tau}$ (R: resistance, C: capacitance of the high pass filter $\tau = RC$: time constant). Since V is the voltage at the input of the inverter, the voltage at the output of the inverter (Vout) is 0V as long as V is above the threshold of the inverter and 5V when it falls below threshold. If we denote a drop from 5V to 0V, followed after a time T by a step from 0V to 5V as a signal, we can say that a signal propagates in time from Vin to Vout. These signals are marked with a *. T can be chosen by choosing R, since T is proportional to R, as explained in the text.

The outputs of these oscillating elements are square wave voltage signals that are used to drive a motor. The outputs of two of the elements that form the ring of the controller (see Figure 3) drive the front motor, and the other two drive the hind motor. The outputs of two elements are connected (via buffers) to the inputs of a motor and the voltage difference across this motor causes it to turn in one direction. When the voltage difference is reversed, the direction in which the motor turns is also reversed. The form of outputs therefore results in moving the motors and thus the legs back and forth in a rhythm that is determined both by the signal duration times of the elements involved in controlling that particular motor as well as by the current mode of the controller (either one or two signals can be propagating through the ring, as shown in Figure 3). This rhythm gives rise to a walking motion. Since the legs of one girdle are attached to each other, the phase between them is fixed at 180°. The two possible modes of the controller yield two different gaits (see Figures 3 to 5). Asynchronicity of the outputs of the elements in the ring, induced by non-identical time constants, can be used for turning behaviour. The time constants of the elements can be individually modified in real-time by simple sensors that change a resistance. Therefore sensory information can be used to directly modify the machines behaviour.

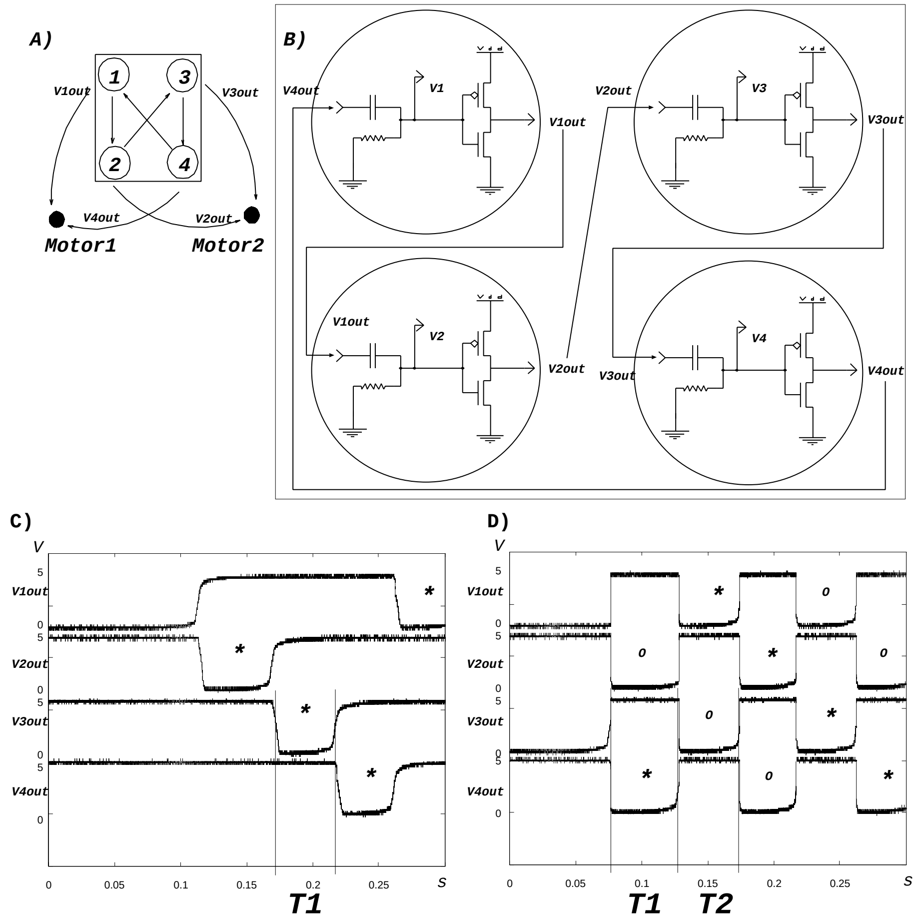

Figure 3: A) Schematic of controller circuit; the circles stand for the basic elements shown in Figure 2. They are coupled together in a ring, the output voltage of one element being the input-voltage of the next. B) shows the entire control circuit in detail. In this coupled oscillator ring two modes can be observed. C) and D) show the measured output voltages V1out to V4out in each mode that drive the motors (via buffers). Depending on the initial conditions, there can be one signal (of length T1, marked with *) propagating through the ring, as shown in C), or two signals (of lengths T1 and T2, marked with ^{o} and * respectively) as shown in D). All signal times depend on the time constants of the single high pass filters as described in the text. They can therefore vary from inverter to inverter and the signal durations can be asynchronous. Connected to the motors as shown in A), we obtain two different gaits. A slow walk in case C) and a faster trot in case D). Figure5 and 4 respectively show this.

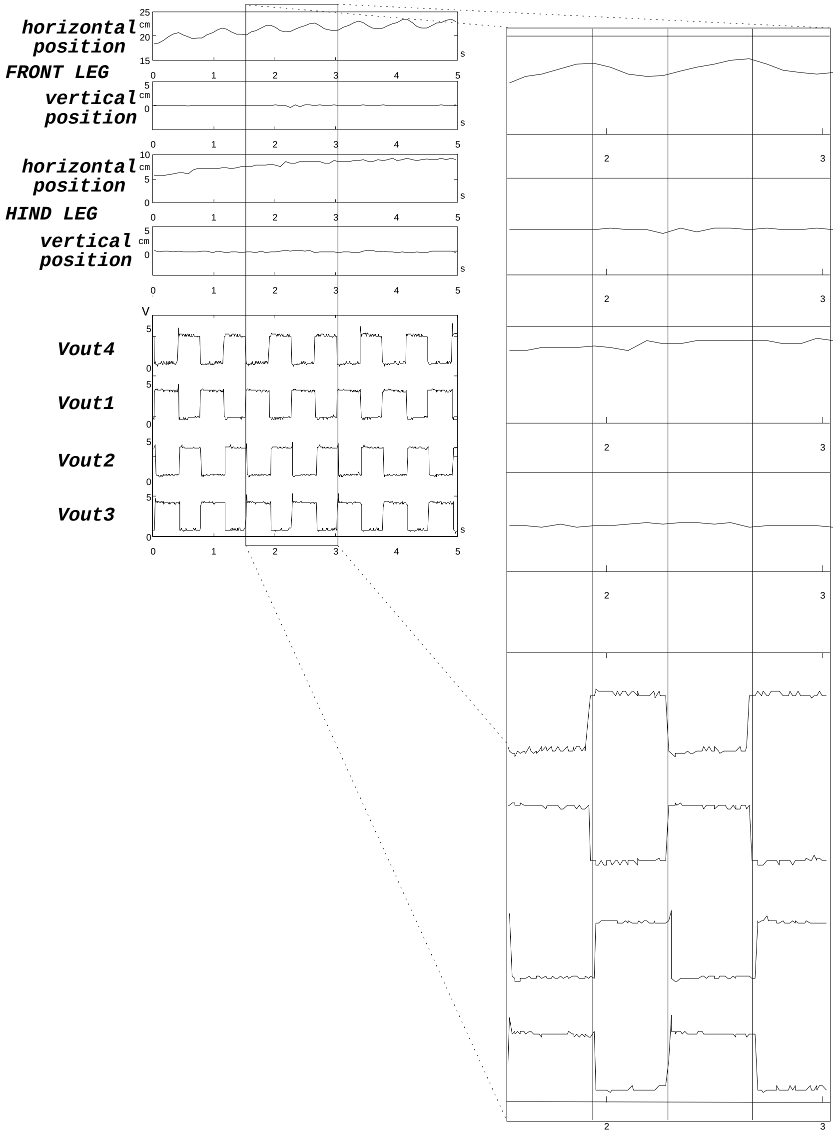

Figure 4: Data of leg trajectories and internal voltages of the walking robot (trot-like gait). Two cycles are enlarged for clarity. For details see text.

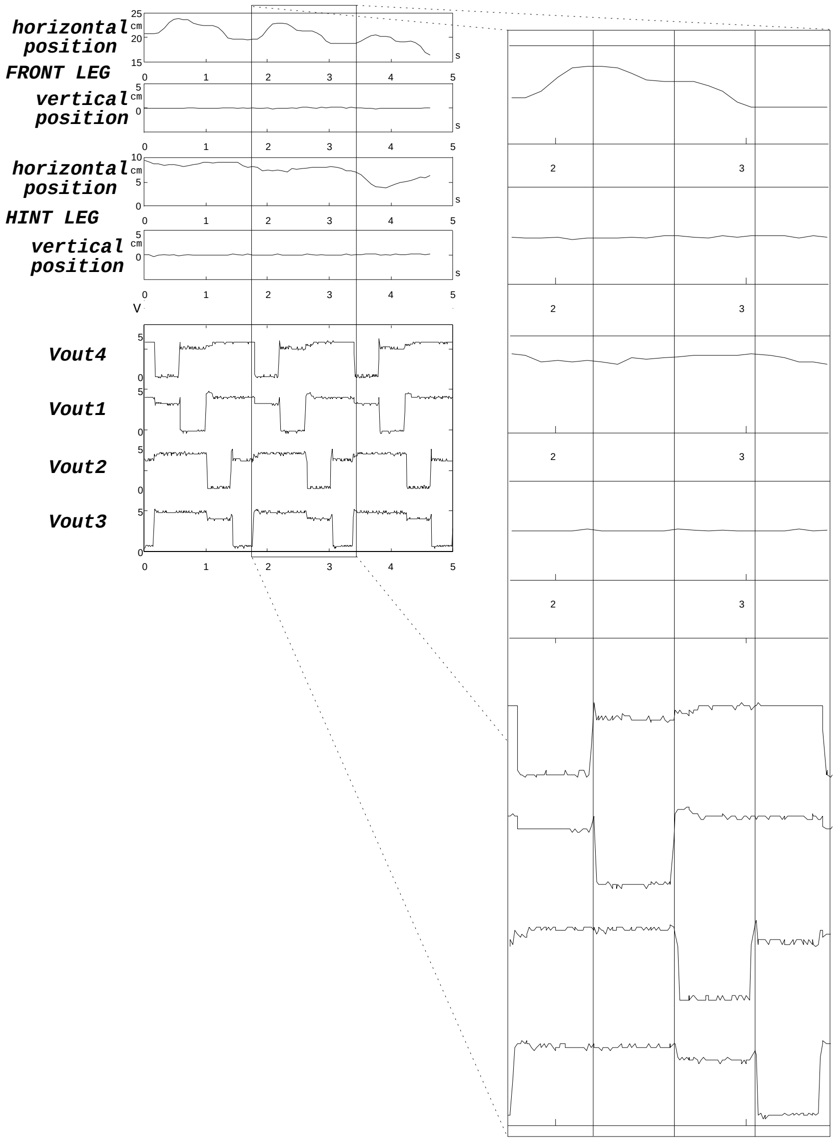

Figure 5: Data of leg trajectories and internal voltages of the walking robot. One cycle is enlarged for clarity. For details see text.

4 Methods

For observation of the robot's behaviour, data is acquired by simultaneously recording the trajectories of the robot's feet and the internal state of the controller. LEDs are attached to the robot's feet on one side of the machine. A CCD-camera monitors the robot from one side and an algorithm tracks the bright spots caused by the LEDs. We thereby obtain the horizontal and vertical positions of the legs as a function of time. The horizontal position of the feet indicates forward motion while the vertical position shows their lift. The internal states are represented by the voltages at several nodes of the controller as a function of time. Here we chose to measure the output signals that drive the motors in order to show the causal relationship between these voltages and the foot trajectories. Data was recorded for both modes of the controller to show the two different resulting walking-gaits.

5 Results

Figures 4 and 5 show the data recorded from the operating robot while its controller is in the two different modes, that were shown in Figures 3 D and C respectively. The upper trace of each of Figures 4 and 5 shows the horizontal displacement of the left front foot (positive displacement is in the direction of motion of the robot) as a function of time, the second trace shows the vertical position of this foot (where positive displacement means lift), and the third and fourth traces show the horizontal and vertical positions of the hind foot. The traces in the lower half of each figure show the voltage outputs of the oscillators that drive the motors. The upper two of these voltage traces drive the front motor, the lower two the hind motor.

In Figure 4 the controller is in the mode shown in Figure 3 D. The vertical lines in the enlarged part of the figure are intended to indicate the relevant time intervals of a cycle.

During one half cycle of the oscillation the rear motor turns the body into a position that takes weight off the left front leg enabling it to move forward because of the simultaneous movement of the front motor. During this time the front foot can be observed moving forward (first trace). During the other half cycle weight is simultaneously put onto the left front foot by the movement of the hind motor and the foot is also moved backwards by the front motor. This makes the robot travel forward as expressed in a total positive displacement of front and hind foot in the horizontal direction during one cycle. The small velocity of this motion was chosen deliberately for practical reasons.

If the friction between the left front foot and the ground was ideal, we would not see the backward movement that is due to slip. Instead we would only see the hind leg being dragged forward during this part of the cycle. The hind foot moves forward in a rather continuous fashion, showing slight backward movements due to slipping. The vertical displacement of both observed feet is negligible; variations mainly expressing the error in the tracking measurement. This means that the shift in weight between the front legs, induced by the movement of the hind motor, is not sufficient to lift the hind feet up. The symmetry of the gait resembles that of a trot.

Figure 5 shows the data for the second possible mode of the controller. In this case we observe a much slower movement of the robot and we see that it moves backwards.

Looking at the voltage traces, we observe that the left front foot moves forward, when the output of 'element 4' of the ring (V4out) is low, because this causes the front motor to turn the left leg forward. Also the hind leg moves backwards due to slip. During the next time interval the signal that propagates through the controller causes the next output-node to be low. This turns the front motor back, therefore moving the front foot backwards. During the following time interval the hind motor turns the hind left leg downwards, thereby lifting weight from the front left leg and enabling it to slip further backwards. In the last time interval the hind motor turns in the other direction, which does not effect the front left leg, but causes the hind left leg to move backwards. This movement results in a total negative displacement of the robot in the horizontal direction. The total velocity is significantly smaller than in the first case (Figure 4). This gait resembles a backward walk.

6 Conclusion and Outlook

We have explained the design of a controller for 4-legged machine walking and tested this controller on an actual robot. Moreover we have shown that the controller displays the expected behaviour and leads the robot to locomote with either of two different gaits. The mechanics of the robot as well as the connections between the output voltages and the motors determine which gaits will be observed in the walking machine. This particular implementation leads to a rather quick forward movement in one case and a slow backward movement in the other. The gaits can be switched by changing the initial conditions of the oscillation. This can, for example, be done by a tactile sensor that briefly connects an input node of one of the inverters to V_{dd}. A possible use of this behaviour is having the robot back away from obstacles it runs into. Other sensory information can modify the controllers behaviour directly via changes in resistance, causing changes in the duration of the output signals and therefore changes in the coordination of the leg movements. These can, for example, lead to turning behaviour. A tactile sensor monitoring one side of the robots body can therefore cause it turn away from sensed objects (or towards them, depending on the bias chosen by the designer) and likewise a set of photo-diodes, monitoring both sides of the robot, can result in a phototropic (or photophobic) behaviour. Use of sensory information of this kind is subject to further discussion elsewhere.

We have already described some limitations that arise from mechanical problems, such as the lack of friction between feet and floor. The disadvantages of the controller are firstly, that the phase of the movement of one motor relative to the other is limited. It is not possible to achieve any phase lag between them. For smooth, stable walking one would like to be able to control the activity of the motors in such a way that an overlap of variable phase difference is possible. Secondly one would like to be able to model more than two gaits. Both of these disadvantages are addressed by work in progress.

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