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Combining central pattern generators and reflexes

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ABSTRACT

Locomotion of quadruped robots has not yet achieved the robustness, harmony, efficiency and flexibility of its biological counterparts. Biological evidences showed that there is a two-way interaction between the Central Pattern Generators (CPGs) and the body in the locomotion process of animals. Therefore, the development of bio-inspired controllers seems to be a good and robust way to obtain an efficient and robust robotic locomotion. This contribution presents an innovative hybrid controller that generates locomotion through the combination of CPGs and reflexes. The results show that the hybrid controller is capable of producing stable quadruped locomotion with a regular stepping pattern. Furthermore, it proved to be able to deal with slopes without changing the parameters and with small obstacles, overcoming them successfully.

1. Introduction

Legged animals present an efficient and harmonious locomotion, capable of walking and running on unstructured terrains, with obstacles, holes and slopes. Animal's ability to deal with real world situations have always fascinated researchers, compelling them to understand what natural mechanisms are responsible for the generation of simple movements like walking and running, but also more complex and intelligent motions. The development of bio-inspired controllers seems to be a good and robust way to obtain an efficient and robust robotic locomotion, mimicking their biological equivalents.

Despite current and intensive research, locomotion of quadruped robots has not yet achieved the harmony, flexibility, efficiency and robustness of its biological equivalents, and, therefore, its development seems to be crucial. The generation of locomotion on unpredictable terrains is a big challenge, one that traditional methodologies were not yet able to successfully solve, and the biological evidences recorded over the years give us sufficient bases and support to develop bio-inspired robots.

It is known that locomotion in animals is generated at the spinal cord by a combination of CPGs and reflexes. CPGs can be simply defined as biological neural networks capable of producing rhythmic patterns in the absence of sensory information. On the other hand, reflexes are events triggered by sensory signals. How exactly this combination is made in animals is still unknown, however, this work proposes a network which combines both identities.

The proposed closed-loop control strategy proposes to introduce CPGs, modeled by nonlinear oscillators, as gait modulators on top of a reflex-based model.

On one hand, the combination of CPGs and reflexes can bring greater responsiveness of the robot to all types of disturbances through the reflexes. On the other hand, the presence of CPGs enable a supervisor that predicts every movement and, thus, is to correct disabilities found during locomotion, such as system noise and sensory feedback failure. This approach is sustained by the existent and ever growing consensus that both intrinsic and sensory feedback signals play a crucial role in controlling the act of locomotion [1]. It is also largely supported and inspired by biological evidence, in which it is believed that the CPG provides for an internal model of the controlled mechanical oscillations during locomotion, *i.e.*, it contains the input–output relationship (internal model) of the motor behavior it controls. Additionally, there is also biological evidence that there is a two-way interaction between the CPGs and the body, such that the CPGs actively process sensory inputs, and mechanical factors contribute to their entrainment [2]. In such case, CPGs could instead be interpreted as generators of oscillatory signals as a means to decode sensory information, instead of producing motor commands in a feedforward manner.

Some projects were carried comprising CPGs and reflexes [3,4]. Often, CPGs are the central mechanism responsible for direct motor generation, and reflexes had the function of regulating/modifying the CPG's activity. In our approach, CPGs have an alternative role, serving as predictors of motor actions, providing an internal model of the limbs movements. Therefore, CPGs are capable of filtering the errors from sensory information, producing a more robust locomotion, at

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the same time being very adaptable to the real world, since the controller has a reflex network that generates motor actions through the robot's interaction with the environment.

All aspects previously expressed show the relevance of this field, presenting an innovative character, contributing to the scientific community with advancements able to help answer some important questions. For instance, how reflexes are combined with CPGs and what is the role that each part performs in the locomotor system. Main innovation comes from the hypothesis of using CPGs as feedback predictors, following an idea from Kuo [5], in which the CPG component is derived from the feedback pathways, and then modulate their timing, amplitude and duration.

An important study of More et al. [6] shows that the CNS should have an internal model capable of predicting the best future motor actions, compensating the internal delays existing in animals. We based our hypothesis in this study, in which the feedforward component of the hybrid controller should predict the motoneurons activity, improving the robot walking behavior. Additionally, based on Kuo work [5], we also hypothesize that the hybrid controller must be capable of increasing the walking stability, providing a more robust and efficient locomotion.

This paper is structured as follows. Firstly, both the current state of the art and the current work are discussed in more detail. Section 2 shows the most important biological evidences applied in the proposed controller. Section 3 presents the developed hybrid controller. The achieved simulation results are discussed in Section 4. Finally, are presented the conclusions and future work.

1.1. State of the art

Over the past fifty years, engineering has presented good solutions to generate stable locomotion, which can be achieved by simple mechanical models consisting of a mass bouncing on weightless limbs, in which the dynamics of these models resembles an inverted pendulum [7,8]. These mechanical models or passive walkers can serve as templates for the description of locomotion, but they cannot predict the locomotor frequency and energy expenditure in overground walking. Therefore, it is necessary to complement passive walkers with muscles' models and sensory feedback [1].

On the other hand, biological evidences proved that feedback pathways and CPGs act jointly in the generation of locomotion [5] and, therefore, the question arose of what would be the advantages of combining these two concepts.

Waden and Ekeberg [4] presented a neuronal model of a single quadruped robot leg combining properties of mechanical and neuronal systems. The locomotion was centrally generated and had some reflexes that could improve the leg movements such as Anterior Extreme Position (AEP), Posterior Extreme Position (PEP), Ground Contact (GC) and Stretch reflex. In the same year, Cruse et al. [9] developed a controller of a hexapod robot, inspired on reflexes, which generated locomotion based on sensory information. Kimura et al. [10] presented their first attempt to build the Patrush quadruped robot, capable of walking dynamically on uneven terrains, using bio-inspired nervous system models based on concepts of CPGs and reflexes. Kuo [5] used a simple pendulum to study the combination of the feedforward (CPG) and feedback components in locomotion and developed a Hybrid Feedforward/Feedback System, which exploits the advantages of combining the two components. Fukuoka et al. [11] presented a quadruped robot called Tekken, that was capable of walking with medium speed on uneven terrains. This work was extended in Tekken 2 [3]. The robot was able to move in an unknown outdoor environment. Yakovenko et al. [12] developed a planar locomotor model of two hind limbs to estimate the stretch reflex influence in locomotion. The leg control system included two components: a CPG and a stretch reflex. Hartmut Geyer and Hugh Herr presented a human locomotion model controlled by muscle reflexes that exploited the principles of legged mechanics [13]. Recently, Klein and Lewis [14] presented a neural controller implemented with CPGs and reflexes, employed in a bipedal robot that models the human muscular architecture. Owaki et al. [15] presented simple quadruped robot named Oscillex 2 to understand the interlimb coordination mechanism capable of generating locomotor patterns. Finally, Dzeladini et al. [16] presented an extension of the neuromuscular model of human locomotion developed by Hartmut Geyer and Hugh Herr [13]. They introduced CPGs as a feedforward component, in which CPGs should be able to reproduce feedback signals generated by a stable walking gait of the model presented by [13].

From an engineering perspective, a stable and efficient locomotion is better achieved with feedback, since feedback signals can compensate for unexpected disturbances, as opposed to pure feedforward controllers [5]. Furthermore, the studies of Kuo [5] and Dzeladini et al. [16] suggest that one can achieve greater flexibility when combining CPGs and reflexes in a non-standard way.

In this contribution, we present a controller to generate quadruped locomotion that comprises and combines two biological concepts: CPGs and reflexes. The sensory-driven controller [17] resorts to the minimum number of reflexes and is able to produce a successful walking behavior. This includes the ability to deal with stumbling in objects and descending slopes. CPGs are used as predictors of the motor actions that would be generated by reflexes. Their combination is achieved by having the CPG acting as an internal model of limb motion which predicts the state of the limb. The CPG is entrained by a feedback sensory signal, acting as an error signal, which will accelerate/deaccelerate the CPG. Therefore, CPGs are capable of filtering the errors from sensory information, producing a more robust locomotion, at the same time being very adaptable to the real world, since the controller has a reflex network that generates motor actions through the robots interaction with the environment. We apply CPGs with a different interpretation, since they are no longer used to generate oscillatory signals to produce feedforward motor commands, but rather to assist the decoding of sensory information.

Related work in biped is presented [16]. The main differences and advantages of our work are (1) the absence of phase reset mechanisms which are replaced by a phase modulator mechanism [15]; (2) the online adaptation which is very relevant; and (3) the proposed CPG acts at the motor level instead of acting at the sensory feedback level.

Several research questions are herein addressed. The combination of both CPGs and reflexes is expected to favorably increase the stability and harmony of the robot locomotion, thus generating a more stable, regular and robust locomotion. The achieved performance will be assessed through gait analysis. The system will be tested and evaluated focusing on robustness to perturbations. Specifically, by verifying the system ability to deal with perturbations without falling, and the ability of the CPG mechanism to act as a noise filter and thus generating a gait disturbed as little as possible. Additionally, both delay and noise will be included in order achieve a more realistic and robust model and to verify the robustness of the proposed model to a more realistic scenario. Experiments will also be delineated to elicit the role of the feedforward component in predicting the robot motor actions by addressing the possible benefits that the CPG inclusion brings to the model. Thus, this work studies the relative importance of the different feedback/feedforward pathways. Emphasis will be given to the analysis of each feedback pathway and its combination with the feedforward predictor, as well as to the increase in robustness. Finally, the controllers ability to exhibit a biologically consistent trend of increasing/decreasing gait cycle network for increasing/