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Prototype, control system architecture and controlling of the hexapod legs with nonlinear stick-slip vibrations

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ABSTRACT

The paper introduces the constructed prototype of the hexapod robot designed based on the biomechanics of insects for inspection and operation applications as well as for different research investigations related to the walking robots. A detailed discussion on the design and realization of mechanical construction, electronic control system and devices installed on the robot body are presented. Moreover, the control problem of the robot legs is studied in detail. In order to find the relationship between movements commonly used by insects legs and stable trajectories of mechanical systems, first we analyze different previous papers and leg movements of real insects. Next, we are focus on the control the robot leg with several oscillators working as a so-called Central Pattern Generator (CPG) and we propose other model of CPG based on the oscillator describing stick-slip induced vibrations. Some advantages of the proposed model are presented and compared with other previous applied mechanical oscillators with help of numerical simulations performed for both single robot leg and the whole robot. In order to confirm the mentioned numerical simulations, the conducted real experiments are described and some interesting results are reported. Both numerical and experimental results indicate some analogies between the characteristics of the simulated walking robot and animals met in nature as well as the benefits of the proposed stick-slip vibrations as a CPG are outlined. Our research work has been preceded by a biological inspiration, scientific literature review devoted to the six-legged insects met in nature as well as various prototypes and methods of control hexapod robots which can be found in engineering applications.

1. Introduction

Legged locomotion is very popular in nature and lots of animal species use this way for traveling on Earth. Probably for this reason also multi-legged walking robots (inspired by walking animals) belong to the important group of mobile robots found in engineering applications [1,2]. Walking robots are good mobile machines capable of traversing over irregular and uneven terrain, including obstacles and gaps, while providing many degrees-of-freedom (DOF) if manipulation tools are required [3]. It should be emphasized that though multi-legged walking robots require additional effort to control their locomotion, they (similar like crawling robots) can go, where the wheeled ones cannot. From a viewpoint of application this is why different types of a biologically inspired multi-legged robots are required in engineering and can be used for exploration of the highly broken and unstable landscapes [4]. There are a lot of examples of biological inspirations and constructed robots in the scientific literature, and interesting and compact state of the art in this area can be found, for instance, in one of the recent paper [5]. Based on the latter reference and many others cited therein important papers a brief summary devoted to biological paragon from nature, methods of investigations of locomotion, as well as the constructed multi-legged robots, is presented.

The first gait studies were based on the observation of animals in nature. In 1899 Muybridge used 24 cameras for studying the motion patterns of the running horse [6], and at present the cited paper is treated as classical one in the study of walking gaits [5]. Since then, a number of experimental observations of other animals (including reptiles, amphibians and insects) were conducted, and on the basis of the observation was attempted to use their movement in different walking machines. For instance, insects and spiders are relatively simple creatures, which are able to successfully operate by using many legs at once in order to navigate a diversity of terrains and they served as an inspiration for numerous researches [7–12]. Studies conducted in papers [13,14] were inspired by the movements of the cockroaches. Paper [15] presents both simulation studies and physical results obtained on the implementation of a model of praying mantis behavior on a robotic hexapod equipped with a real time color vision system. In turn,

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for instance in papers [5,16,17] the authors used crab gaits as a biological inspiration for the constructed robots. Despite the passage of many years since the first observations made by Muybridge this kind of experimental research is still used by contemporary researchers, for instance in the mentioned earlier paper [15]. Using video camera also in one of the recent paper [5] the motion features of the biologic crab are studied, including both transfer and support phases, as well as transition between them. It should be noted that in addition to experimental studies simultaneously mathematical methods describing the legged locomotion system were developed. First, a good mathematical foundation in this area was presented by the authors of the paper [18]. McGhee [19] proposed (new, as for those times) mathematical description of gaits and demonstrated an enormous amount of possible gaits of multi-legged animals (the so-called McGhee formula). Since that time, still appear different and offered by many researchers mathematical models for the testing of the multi-legged robots, both in terms of construction and control.

There are a lot of different types and prototypes of legged robots which can be found in the literature, namely: bipeds, tripods, quadrupeds, hexapod, or octopod [3]. An interesting literature review of the most important and the most known multi-legged robots can be found in [5]. Studies of multi-legged robots have been initiated in 1960s by McGhee and Frank [20], who constructed the first four-legged robot named “Phoney Pony”. Since that time a wide variety of four-legged (quadruped) robots have been built, including: TITAN-VIII [21]—the robot driven by wire-pulley system, BISAM [22]—the self-adaptive quadruped robot, SIL04 [23]—the robot driven by DC servomotor with torus worm gear, Tekken [24]—the robot controlled by the system including CPG and reflection mechanism, ARAMIES [25]—the robot for working in non-structural environment, and BigDog [26]—the robot designed for transport of military materials. In this paper we present only the most interesting and well-known prototypes of the six-legged robots, which are still very popular and most widely studied. First, an anti-torpedo, amphibian multi-legged crablike robot called ALUV has been constructed in 1990s [27]. Other constructed hexapod robot, which can walk like crab and also possesses the ability of anti-overturn, is the robot called Ariel [28]. Next, important hexapod robot inspired by crab and called Lemur was modeled by imitating body similar to the body of octopus with crab legs [16]. In order to detection and removal of the landmines, the six-legged walking robot called COMET-III that ensures stable walking in the mine field has been constructed [29,30]. Later, a military six-legged robot named as SILO-6 primarily for terrain mine-clearing has been built [31,32]. In turn, in order to explore unknown celestial body in the outer space, different prototypes of the hexapod robots were also constructed, namely Genghis [33], Hannibal [34] and Attila [35]. Yet another interesting type of six-legged robot is the RHex robot—a biologically inspired hexapod runner that travels better than one body length per second and uses a clock excited alternating tripod gait to walk and run in a highly maneuverable and robust manner [4]. In turn, SensoRHex is a modified and functionally improved version of the original RHex robot, which possesses six half circular rotary compliant legs, and each of them is actuated by a gearbox DC motor controlled in a position or current (torque) mode [36]. The paper [37] introduces the manufactured by the authors hexapod robot called ROBOTURK SA-3, which can be used as both the quadrupedal and hexapod robot. In one of the recent paper [38] a novel hexapod robot called HITCR-II, characterized by high-integration and control with multi-sensors and suitable for walking on unstructured terrain, is proposed. Agheli et al. [3] introduce SHeRo, a scalable hexapod robot designed for maintenance, repair and operations within remote, inaccessible, irregular and hazardous environments. On the other hand, a novel Abigaille-III hexapod robot powered by 24 miniature gear motors, which uses dual-layer dry adhesives to climb smooth and vertical surfaces, is presented by Henrey et al. [39].

Recently, also eight-legged robots have become popular, and as examples we can list [5]: a biomimetic eight-legged robot SCORPION [40] and searching and rescuing robot Halluc II [41]. The SCORPION robot consists of three main body parts and eight homogenous legs, and the joints of legs are actuated by standard DC motors with high gear transmission ratio for sufficient lifting capacity. The control system of the mentioned robot combines the CPG and the reflex. In turn, Halluc II is a robotic vehicle with eight wheels and legs designed to drive or walk over rugged terrain, which is also provided with wireless network capabilities and a system of cameras and sensors that monitor the distance to potential obstacles. In result, the robot constantly assesses how best to adjust the position of its legs and wheels.

Though the mentioned eight-legged robots become very popular and each of them certainly possesses interesting original features, however, it should be noted that eight-legged robots are usually studied based on six-legged robots to imitate some specific animals [5]. Hexapod robots due to their simplicity, static balance greater than in case of four-legged robots, with various configurations and leg designs, have engaged a number of researchers. Six-legged robots imitating insects make their movements using six legs and according to the McGhee formula [19] have an especially great spectrum of different types of gaits. However, it is difficult to define and describe all gaits that insects or hexapod robots can use. In all cases of the mentioned gaits some of the legs are performing swing movements in the air, while the rest are supporting and propelling forward the body on the ground. Generally, six-legged robots have superior walking performances in comparison with those having fewer legs, especially in terms of larger statical and dynamical stability, greater walking speeds or lower control method complexity (a control of their legs still does not belong to easy tasks). Since for keeping the stability of the robot only three legs are sufficient, hexapod possesses the great flexibility in walking. To maintain a balance of the robot only three legs are enough, but to perform a movement four legs are required. Thus, in case of failure of two extremities, hexapod can still continue his motion. Probably this is why over the last 30 years an extensive research has been conducted in this field, and different prototypes of hexapod walking robots have been constructed and investigated. Finally, it should also be noted that analysis of gait algorithms used in six-legged robots is similar to that regarding the case of four-legged ones. Moreover, the mentioned gait analysis can be relatively simply extended and applied to eight-legged robots.

On the basis of presented above brief literature review, one may can conclude that analysis of walking robots, especially hexapod robots, still belong to challenging tasks of many researchers. Walking robots have a greater ability to adapt to various kinds of terrains in comparison with wheeled or tracked ones [42]. New constructions of walking robots still arise, and to control their movement still CPGs are used. In addition, currently built structures are usually equipped with various types of measuring or actuating devices which expand their application possibilities. In addition to the operational capacity of the constructed prototypes an important issue concerns the energy consumption of these systems. Minimization of the mentioned energy consumption extends time of the robot work, which often plays a key role to carry out the realized mission. This paper issues and research have been inspired by both current trends in mechatronics and the mentioned above requirements for modern robots. As a result, we construct own prototype of the hexapod robot, which can be used both for experimental studies as well as for inspection and operational applications. The robot contains many additional devices installed on its body and a system of wireless data transmission. In this paper we are focused on the general presentation of the mechanical