Doctoral thesis: Biology-Inspired Control of a Walking Robot

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I. Doctoral Thesis

Appropriateness and relevance

The doctoral thesis deals with the design, development, and construction of a hexapod robot inspired by concepts and approaches found in nature, especially in the realm of insects. Given the context of global robotics development, the topic is actual. Robotics and intelligent behaviour and control systems of robots is widely solved problematics in industry, services and space exploration.

The work has 120 pages including an abstract, table of contents and bibliography, it is written in English (except for the Czech abstract) and is divided into 7 chapters. The first chapter provides an insight into the problematics of walking robots and defines the objectives of the work. The second chapter is a study of the structure and some principles of the functioning of the insect body in terms of inspiration for walking robots. The third chapter captures the current state and approaches used in the field of hexapod walking robots. The fourth and fifth chapters, which represent the core part of the work, describe the design and construction of the original hexapod walking robot WHexaR. In the sixth chapter, the experiments performed with this robot, both simulation and real, are described and discussed, focusing on both individual parts of the robot and the functionality of the robot as a whole, as well as on the energy demand of the solution. The seventh chapter brings a summary of the acquired knowledge and conclusion of the thesis.

A summary of the contributions of the thesis

The theoretical part of the thesis is relatively limited (it consists mainly of deriving forward and inverse kinematics of the robot and partially designing the robot's control system), however, the main contribution can be seen in the practical realization and experimental validation of the given concepts, especially the idea of using the trochanter joint to improve stability and reduce energy consumption while moving the robot in sloping terrain, and also movement combining gait and ride. The concept of a hybrid robotic control system combining reflexes with higher-level planning mimicking insect's behaviour, according to the results documented in the thesis, is rather basic, the contribution can be found in the experimental verification of implementing insect reflexes within the robot's movement.

Assessment of student's approach, used methods and the objectives achievement:

In Chapter 1.1, the author declares his intention to propose a new, original design of a robot that imitates the movement and behaviour of insects using acquired experience from his successful bachelor's and master's theses. He set the following five objectives:

1. Study insects with a focus on the nervous system, body and limb structure, behaviour, and movement.

2. Study walking robots with a focus on hexapods, their design, construction, and control.

3. Design a six-legged walking robot whose body and leg structure is inspired by the body and limb structure of insects.

4. Design a biology-inspired control system for a walking robot that will be able to adapt the robot's motion to the complexity of the surrounding terrain and mimic insect behaviour.

5. Focus on the speed of walking robots on flat surfaces and the ability to move stably in sloping terrain, with an emphasis on energy-efficient movement.

The author demonstrates a very good understanding of the design, construction, and control of robots, and basic insight into the natural world of insects, their body structure, and nervous system. He provides overview of the current state in the field of walking robots with a detailed focus on hexapod walking robots, justifies and substantiates the benefits of the chosen architecture of the hexapod walking robot in his design. He summarizes the information essential for designing the limb structure, types of actuators, different variants of gaits, possibilities of designing the control system, introduces performance metrics, and metrics for assessing the stability of the robot. He also provides a comprehensive overview of existing walking robots, that creates space for comparing them with his own design. Therefore, the goals numbered 1 and 2 of the work can be considered fulfilled.

In his own design of the hexapod walking robot, he uses the above-mentioned knowledge and the inspiration of the insect body structure, especially in the design of the robot's limbs, thus fully fulfilling the third objective of the work.

In the creation of the robot's control system, the potential of neural network approach was not used due to "insufficient exploration of insect's nervous system" (as author claims in chapter 4.2), although in chapter 3.3.2 there are citations of other authors who cover this area at least partially. If it was solved, even unsuccessfully, it would certainly be worth describing the chosen approach and the problems that led to the rejection of this approach. The focus of the design of the control system thus shifted mainly to the design and implementation of individual reflexes. The higher level of planning and the mechanism for adapting the robot's movement to the complexity of the environment are not sufficiently described and presented in the work. Therefore, the fourth objective of the work was, according to the available materials, only partially fulfilled, and its fulfilment is not sufficiently proven by the described experiments.

The energy demand of the movement on a smooth surface in sloping terrain was sufficiently elaborated and assessed, also in view of the idea of using the trochanter joint to improve stability and reduce the energy demand of the movement. There is a lack of a broader comparison of the achieved consumption parameters (CoT) with other existing robots, although these parameters can be obtained from available sources. Nevertheless, the fifth objective of the work can be considered fulfilled.

Given the limited theoretical part of the work (consisting of deriving forward and inverse kinematics of the robot and partially designing the robot's control system) the main contribution could be seen in the implementation and experimental part if especially the latter was better elaborated. Generally, my objections are aimed at the description of conditions and the realization of the presented experiments, so that they are repeatable based on this description. Many of them are, in my opinion, not sufficiently documented in the work. Here I present some specific examples for supplementing or specifying the description of the experiments:

- Chapter 6.5.2 Riding along a Circle - a detailed description of the experiment is missing, for example, it is not stated what was the diameter/circumference of the circle for the error of 1.5 cm when riding around it.

- Chapters 4.2.2 and 5.4 - it is not described where on the front limbs the IR rangefinders are exactly located, whether they move relative to the robot's body during walking, and how the data from them are used to detect obstacles and decide whether to overcome or bypass the obstacle. Their location of rangefinders is not evident even in the enclosed photo documentation.

- Chapter 6.7.1 – it is not completely clear how exactly the stepping reflex was supposed to work. In the design in chapter 4.2.2, it is described as a reaction to the slip of the limb, in the description of the experiment it is said that the leg was prevented from reaching the target position. If this procedure is supposed to simulate slipping, it would be appropriate to better describe why the experiment was chosen in this way and how it simulates the slipping of the robot's limb.

- Chapter 6.7.2. Elevator reflex – it would be appropriate to better describe how (on the basis of which sensor or values from servomotors) the detection of the situation suitable for activating the Elevator Reflex occurs, what specific replacement movements of the limb are performed, whether the step height is increased iteratively or a step with the maximum possible height is performed, what is the maximum height of the obstacle the robot is able to overcome this way, what is the minimum height of the obstacle when the reflex is activated, what was the success rate of overcoming e.g. stairs with the use of the reflex or without it etc.

- Chapter 6.7.3 Searching reflex – it would be appropriate to better describe or illustrate what strategy was chosen to find an alternative support point, which points, at what position from the original point, what was the success rate of overcoming some suitable route for the verification of this reflex (surface with gaps, or going down the stairs etc.) with this reflex activated and without it.

- Chapter 6.7.4 Obstacles negotiation – it would be appropriate to better describe the configuration of the experiment, e.g. how IR sensors were used for measuring the height and depth of obstacles, what height of obstacles the robot can overcome by normal walking, what was the real threshold for overcoming the obstacle vs. its bypass and how it was determined, whether the robot bypassed the insurmountable obstacle or stopped in front of it.

- Chapter 6.7.5 Terrain Controller and Gait Selector – it would be suitable to better describe this experiment, for example: exactly how the switching between individual types of gaits worked, in which terrain it was tested, whether and how the adjustment to terrain changes was tested (e.g. simple –

difficult – simple pattern) and with which measurable results, what were the tested values of individual thresholds and which threshold values were eventually chosen, and how they differed from the original assumption in the design.

Generally, it is not clear, whether the robot was tested within more complex terrain - going up/downstairs, rugged terrain, changing different types of terrain (to verify the functionality of the Terrain Controller), how obstacle detection worked and what was its success rate (how much of the obstacles the robot detected), which could be presented in addition to the results of individual experiments, for example with a video capturing the robot's passing through such terrain.

In the theoretical part of the work, it would be possible to consider the following additions or topics for discussion during the defense:

- The consistency of forward and inverse kinematics has been verified experimentally (Chapter 6.2), it would be worth considering verifying it theoretically by purely mathematical derivation.

- The idea of reducing the energy demand using the trochanter joint is presented in the work in chapter 4.2.2 purely intuitively and then verified experimentally. It would be worth presenting at least a basic physical / mathematical model, based on which it would be possible to predict the percentage of energy demand reduction and subsequently experimentally verify this prediction.

- In equation (5.5) in determining the mathematical relationship between the output value of the IR rangefinder and the actual measured distance, it would be appropriate to comment whether the chosen high number of decimal places in the resulting coefficient values correspond to the required accuracy in the order of cm.

- Consider how to approach the situation when the gradient of the slope is not parallel to the longitudinal axis of the robot's body in order to ensure the foot tips are parallel to the gravity vector and the sufficiency of solving such a case using the trochanter joint.

<u>Evaluation of the formal aspects of the thesis:</u>

The presented dissertation is written systematically and clearly, and its language level is very good. The readability is also enhanced by the appropriate division of individual chapters and a high-quality formal edit of the work. A point of criticism can be the insufficient description of some experiments to ensure their repeatability, as described above.

<u>Quality of publications</u>

The author's publication list includes 8 publications, 7 of which are directly related to the doctoral dissertation. It consists of 5 conference contributions and 3 articles in journal publications. The core of the work has been adequately published. Overall, I rate the publication activity as good and appropriate for the thesis.

II. Student's overall achievements

<u>Overall R&D activities evaluation</u>:

The author's approach and achieved results and their presentation in the thesis, as well as the author's publishing activity, indicate a scientific erudition and creative abilities of the author. Reservations can be found in insufficient proof of fulfilling one of the goals of the work and in the approach and quality of documenting some of the performed experiments, as described above.

III. Conclusion

In the case of substantiating the missing information and clarifying the uncertainties mentioned above in this review (for example during the defense), the submitted dissertation has the potential to meet the generally accepted requirements for the award the PhD degree (in accordance with Section 47 of Act No. 111/1998 Coll., on higher education institution) and I recommend it for defense.

Brno 19.12.2023

Signature of the reviewer:

Ing. Tomáš ONDRÁČEK Ph.D.

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