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Hexapod Robot Energy Consumption Dependence on Body Elevation and Step Height

M. Luneckas[1], T. Luneckas[1], D. Udris[1], N. M. F. Ferreira[2]
[1]*Department of Automation, Vilnius Gediminas Technical University,*
Naugarduko St. 41–335, LT-03227 Vilnius, Lithuania
[2]*RoboCorp, Polytechnic Institute of Coimbra, ISEC, DEE,*
Rua Pedro Nunes, 3030-199, Coimbra, Portugal
tomas.luneckas@vgtu.lt

***Abstract*—Walking robots are well known for being able to walk over rough terrain and adapt to various environments. Hexapod robots are chosen because of their better stability and higher number of different gaits. However, having to hold the whole weight of the body and a large number of actuators makes all walking robots less energetically efficient than wheeled machines. Special methods for energy consumption optimization must be found. In this paper, hexapod robot energy consumption dependence on body elevation and step height is presented. Three main hexapod gaits are used: tripod, tetrapod and wave. Experimental results show that energy consumption does not depend on body elevation or gait. Although, higher steps increases the power consumption. Therefore, when walking over even terrain, lower step heights along with higher body elevation must be selected for tripod or tetrapod gait in order to surpass ground irregularities but still maintain maximum energetic efficiency.**

***Index Terms*—Legged locomotion, robot motion, robot kinematics, robot programming.**

I. INTRODUCTION

Legged robots, compared with wheeled or tracked robots, have much superior movement characteristics (higher ground clearance etc.) due to greater ability to adapt to rough terrain [1]. Just like most of the animals use legs to move and adapt to nature, legged robots have good adaptability to various environments and terrain irregularities [2]. In addition, robots can survive different conditions, such as hazardous environments, catastrophic territories, space, and high/low temperature. Hexapod robots are one of the most stable walking robots and have a large number of different gaits, which gives user the wider range of control.

However, autonomous movement over rough terrain is a complex task. All walking robots requires a high level of research, control, and parameter configuration before making them available for any real missions like bomb deactivation [3] or cargo transportation [4]. Thus, different legged locomotion control methods are needed to perform well the desired task of the system during walking.

Although despite the fact that hexapod walking robots have great adaptive abilities, it is still considered a highly researchable area. All walking robots tend to use much energy due to having to hold the whole weight of the body and all driving parts [5]. This is very important, especially for autonomous robots, because decreasing power consumption is one of the possibilities to increase work time of a robot without changing or charging the batteries [6]. And until today, still a small number of experiments were carried out to find the most energetically effective methods for choosing gaits and walking parameters for six-legged robots.

Reference [6] shows that in order to minimize hexapod robots energy consumption when walking on even terrain, an energy consumption model must be established. After that, every half of gait cycle, special parameters that define foot trajectories must be calculated. Results provided some power savings, but the computations for real-time situations are still needed.

In order to reach demands for hexapod robot energy consumption, an algorithm for torque distribution was found along with energy consumption model [3]. This experiment was done to erase the mechanical part of the problem and heat loss. Simulation results stated that power usage could be reduced with appropriate walking speeds, duty factors and other parameters. However, compared to some four-legged animals in nature, energy cost is still few times away from any real numbers.

Choosing different gaits and gait parameters are the most important and general factors to be taken into consideration. Thus, the analysis of turning gait parameters of a six-legged robot while doing turn was done [7]. Another energy consumption model was developed. Its purpose was to minimize dissipating energy for feet force distributions. Results showed that, unlike tripod gait which is the fastest, but also very unstable, wave gait is the most energetically efficient and the most stable choice.

Another way to minimize power consumption is by observing animals in nature and applying same movement methods for robots. Most of the animals try to find a position in which they would use the least amount of energy, but still completing the needed task. Even humans have the same tendencies. For example, we change gaits when there is a

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need to move faster; we start running instead of walking which is more energetically efficient. Same experiment was carried out with a live horse. Results showed that changing gaits according to movement speed is very efficient [2]. This is due to energy consumption decrease when animal starts using inertia as a helping force, instead of trying to compensate it.

In this work we present experimental analyses of hexapod robot's energy consumption dependence on robot body's elevation and step height. In order for hexapod robot to be efficient its energy consumption must be minimized especially during its locomotion over rough terrain. When walking over rough terrain robot's body elevation and step height must be controlled accordingly in order to maintain stable and smooth locomotion. Hence this suggests that these parameters may directly influence robot's energy consumption.

II. PREVIOUS WORK

In our previous work [8], we observed the static characteristics of a hexapod walking robot. Energy consumption dependence on number of legs on surface was analysed. Three different cases were studied: six, three and zero legs set on surface. Results showed that energy consumption increases as the number of legs supporting the weight decreases.

Also, we observed the energy consumption dependence on movement speed by repeating the same experiment for a hexapod robot like with the horse as mentioned before. Although the difference is uncanny, the horse has four limbs and our robot has six, experimental results clearly indicated that when optimizing energy consumption of a hexapod robot, gait selection must be taken into account when speed rate gets higher.

However, both experiments were carried out only on even terrain, all parameters were static (body elevation, step height, step length) and the range of speed used was too narrow to gain general knowledge. Energy consumption dependence on all parameters should be analysed before including them in robot configuration. And before using hexapod robot in any real-life missions, it is very important to find the best parameters for robotic motion to minimize energy consumption as much as possible.

In this paper, hexapod robot energy consumption is observed by varying body elevation and step height. Three main hexapod gaits are used: tripod, tetrapod and wave gait. Also, each gait cycle is separated by delay to mark starting points of each gait. Then, energy consumption is calculated.

III. ROBOT MODEL

Hexapod walking robot used in this experiment is shown in Fig. 1.

Main parameters of the robot are: whole weight $M \approx 1.5$ kg; body width $L_w = 83$ mm; body length $L = 193$ mm; and for each leg $L_{coxa} = 68$ mm, $L_{femur} = 80$ mm, $L_{tibia} = 105$ mm.

To control the robot we chose microcontroller Atmega16 with a 16 MHz clock frequency. AX-12 servo actuators were used as driving parts. Each actuator weights 55 g, supports 10 V input voltage, 900 mA maximum current and has a 300° degree working angle with a 0.35° degree resolution. Each leg consists of three actuators, making the total of eighteen and concluding the majority of the robots weight.

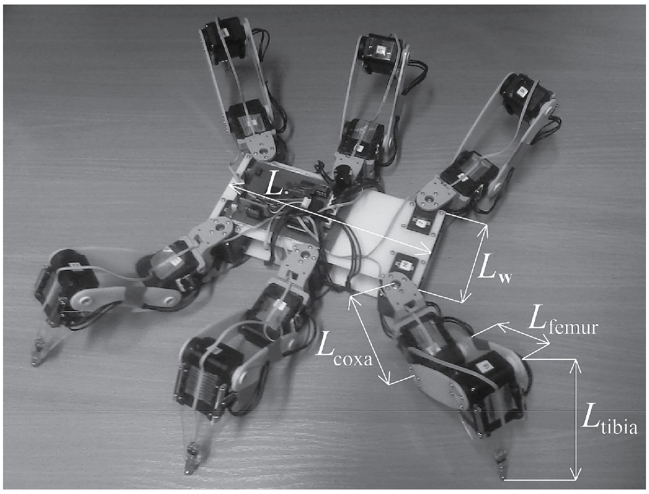

Fig. 1. Hexapod robot model used in the experiment.

Current was measured using a high-side measurement current shunt monitor INA169. A typical circuit was used for measurement with shunt resistor $R_S = 0.1\,\Omega$ and load resistor $R_L = 10\,\mathrm{k\Omega}$ with 1 % precision. This way the output voltage matched load current with ratio 1:1 (1 V equals 1 A). Current was measured between source and the robot giving total current consumed by robot.

IV. ENERGY CONSUMPTION DEPENDENCE ON BODY ELEVATION

In this experiment we chose to use three main hexapod robot gaits: tripod, tetrapod and wave gait. For measuring energy consumption dependence on body elevation, five different heights were used (see Table I). Body elevation values were lower than 10 cm because of mechanical limits.

TABLE I. ROBOT BODY ELEVATION AND STEP HEIGHT VALUES.

Body elevation *H*, cm	**Step height *h*, cm**
2	2
4	4
6	6
8	8
10	10

To eliminate possible power consumption reliance on unneeded parameters, step height and robot speed were set to a constant value for each case: $h = 3$ cm, $v \approx 0.02$ m/s. In addition, 0.5 s delay was implemented inside robots program to find the starting point of each foot transfer phase. Also, signal processing was done by using smooth filter with polynomial order of 5 and 15 points of window.

Current diagrams (Fig. 2) showed no energy consumption dependence on body elevation or gait. The differences between average currents for each gait – $I_{tripod} = 1.8$ A, $I_{tetrapod} = 1.81$ A, $I_{wave} = 1.76$ A – are too small to call any of these gaits more energetically efficient. However, current diagrams with implemented delay between each gait cycle (Fig. 2(a)) reveal that there are two main reasons when most power is being used:

1. Legs are raised to make a step and move forward. Each legs transfer phase is separated by numbers 1–6 (Fig. 2). Transfer time t_t for each leg is $t_t \approx 0.7$ s. Delay time $t_d = 0.5$ s;
2. During each transfer phase feet are pressed against the ground when lowering the leg. Pressure moments are separated by black circles (Fig. 2). Pressure time t_p is half the transfer phase time and is equal to $t_p \approx 0.35$ s.

First problem is not something that could be easily eliminated. This is because legs have to be transferred. So far there are no other methods for movement other than leg transferring. However, the second problem could be fixed by simply using for example force sensors on each of robots foot. Sensors would allow user to control the force by which robot presses its feet against the ground giving the possibility to reduce current peaks.

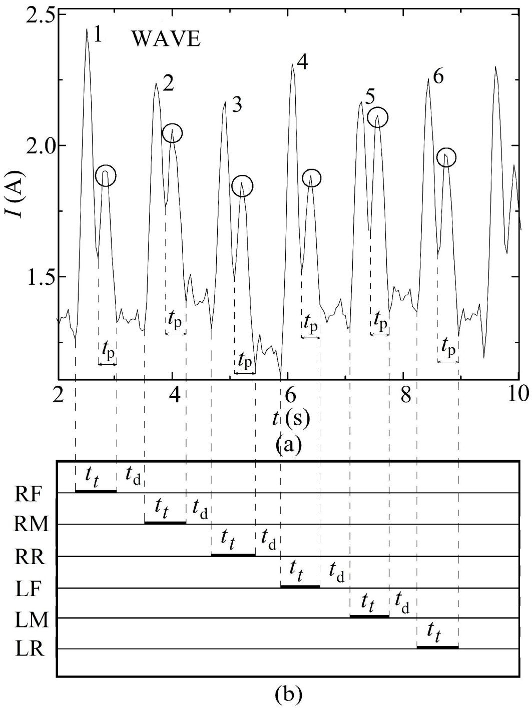

Fig. 2. (a) Current diagram with delay between each legs transfer phase for wave gait. Numbers indicate cycles of each gait. Circles point out the moment when robot presses its legs against the ground. (b) Wave gait phases of legs: RF – right front, RM – right middle, RR – right rear, LF – left front, LM – left middle, LR – left rear.

When measuring energy consumption dependence on step height, body elevation was set to $H = 10$ cm. This value was chosen to imitate robots ability to overcome irregular terrain. Five different step heights were used (Table I).

Current diagrams for all three gaits are shown in Fig. 3. The difference between the lowest and the highest step height is small. But because energy consumption is proportional to current it is enough to determine that energy consumption does depend on step height. The higher legs are raised, the more energy robot consumes. This can be explained by actuator speed increase. The higher legs are raised the faster actuators have to move.

V. ENERGY CONSUMPTION DEPENDENCE ON STEP HEIGHT

To calculate energy values E, we used the same equation as in our previous work

$$E = \frac{U \cdot I \cdot L}{v}, \tag{1}$$

where U – voltage for all actuators, I – average current for each of the cases, L – walking distance, and v – movement speed. The supply voltage $U = 10$ V and we chose $L = 10$ m because this is a normal working distance for a robot this size. In addition, linear fitting was applied to see the precise energy consumption difference between each gait.

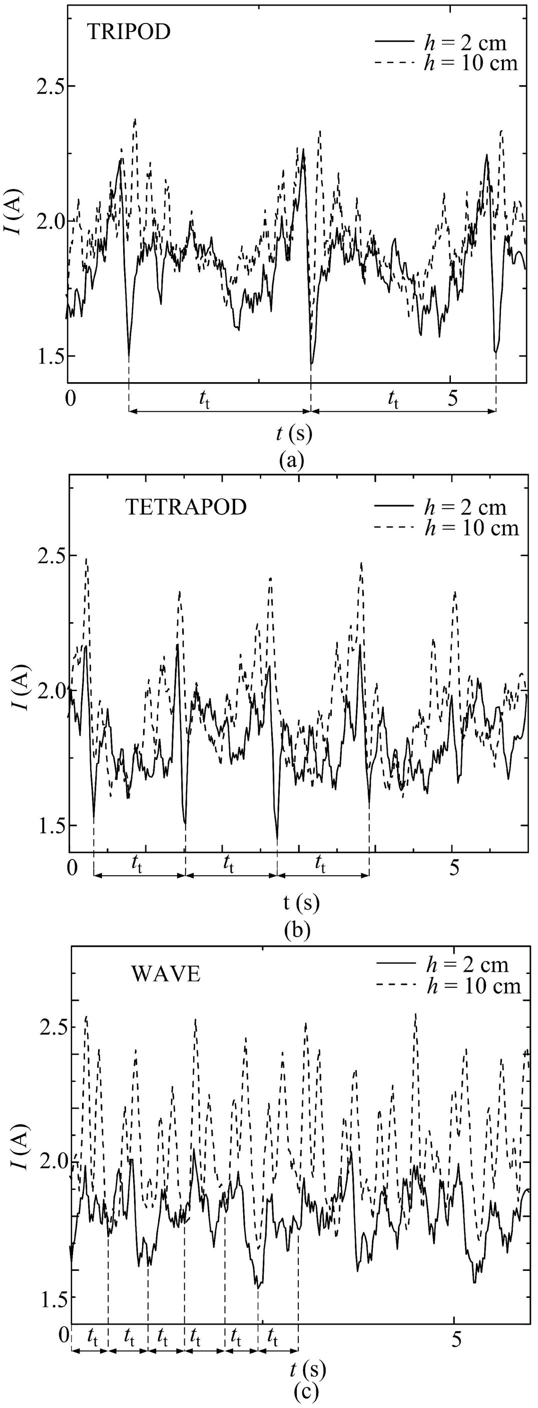

Fig. 3. Current diagrams with no delay: (a) tripod gait, (b) tetrapod gait, (c) wave gait.

Energy values were calculated for all gaits and each step height and are shown in Table II.

Energy consumption dependence on step height is shown in Fig. 4.

TABLE II. ENERGY VALUES FOR EACH STEP HEIGHT.

	Tripod	**Tetrapod**	**Wave**
***h*, cm**	***E*, Wh**		
2	1.27	1.26	1.25
4	1.28	1.29	1.29
6	1.30	1.31	1.32
8	1.31	1.33	1.38
10	1.33	1.34	1.42

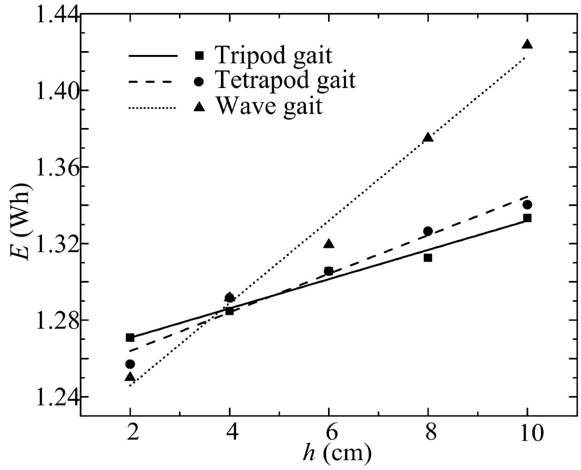

Fig. 4. Energy consumption dependence on step height. Body elevation set to H = 10 cm.

The diagram shows that the higher legs are raised, the more energy robot consumes. And among three gaits, wave gait is the most energetically inefficient, whereas tripod and tetrapod gaits use almost the same amount of energy. All gaits differ by number of phases. Tripod gait has two phases, tetrapod – three phases and wave – six phases. That is why current graph has six peaks (Fig. 2). Also, all gait periods take the same time. And because throughout the gait period all six legs have to be transferred, actuators have the highest speed for wave gait.

Another important thing seen from Fig. 4 is that each line has a different slope. In this case, slope suggests the idea of energy consumption stability. That means that power consumption increases faster when step height increases. It is clear from Fig. 4 that wave gait is the least energetically stable. Tripod and tetrapod gaits are the most energetically stable. Energy consumption stability depends on how fast legs are transferred during the motion. It was said earlier that wave gait has only one leg being transferred over one phase which leads to higher number of current peaks and faster actuator speed.

VI. CONCLUSIONS

Hexapod robot energy consumption dependence on body elevation and step height was observed in this paper. Tripod, tetrapod and wave gaits were used. Five different body elevation and step heights were selected. When measuring power dependence on body elevation, short delay was incorporated between leg transfer phases to understand the beginning of each transfer phase. Energy values were calculated for particular movement distance L = 10 m what is logical for our hexapod robot model.

Results show that energy consumption does not depend on body elevation or gait. Current diagrams with delay showed that most power is used when legs are being raised and feet are pressed against the ground. However, energy consumption does depend on step height. The higher legs are raised, the more power robot consumes. Energy calculations showed that the most energetically inefficient gait is wave and the most energetically efficient is tripod gait. This is because during wave gait actuators have the highest speed and during tripod gait – the lowest.

Overall review of the experiment led to few possible solutions for minimizing energy consumption of a hexapod robot:

1. Each foot could be upgraded with sensors (force sensors etc.) to indicate the moment the foot reaches the ground and to let user control the force by which robot presses against the ground to avoid unwanted current peaks.
2. Tripod or tetrapod gait must be selected along with lower step height when placing feet on even terrain. That way robot uses the least amount of energy. Also, some terrain irregularities can be surpassed if body elevation was set to higher value.
3. Special robot movement algorithm could be implemented to maintain body level and diminish supporting feet sliding backwards to eliminate high current peaks when legs are being raised.

Future work aim is to observe energy consumption on more parameters such as speed or payload. In addition, measuring power consumption of each individual actuator on one leg would give information about parts of the legs that use most energy. Also, using slope for calculating energy consumption dependence on plane slope would give useful data on how robot movement should be improved and prepared for real missions over rough terrain.

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