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EFFICIENCY ANALYSIS IN THE DESIGN OF WALKING MACHINES

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The problem of energy efficiency in the design of walking machine is discussed in this paper. Attention is paid to the calculation of motor powers, gear ratios and to the choice of energetically efficient leg configuration. The motor power is evaluated basing on the knowledge about the range of reaction forces during the hexapod movement, assuming that the body moves at the constant velocity, maintaining the height of the centre of gravity above the ground what is expected of hexapods. The results presented were applied to the walking machine being currently built.

Key words: energy efficiency, walking machines, design methods

1. Introduction

One of the serious problems encoutered by the walking machine designers is optimization of the energy consumption. Mechanical efficiency of locomotion of the existing walking machines is very poor in comparison to the living animals as well as in comparison with the wheeled locomotion. Referred to the living world the expectation is that in the future the artificial legged locomotion will be one of the most energetically effective sources of transportation. Currently the designer of a walking machine must consider the energy consumption which influences the choice of mechanical structure, propulsion and power system.

The sources of energy dissipation in legged locomotion are as follows (Todd, 1985):

- Loss of energy which must be applied to the whole machine to make a leap

- Loss of kinetic energy which must be applied to the limbs to make them oscillate
- Soil compaction, and other forms of motion resistance, power wasted in supporting the body against gravity and other forces
- Geometric work (the hip actuator must work against the direction of motion of the thigh, to brake it at the end of its stroke: this is called the geometric work)
- Inefficiency of actuators and power sources
- Opposing actuators: it may happen, particularly if there are many legs that they do not all thrust in exactly the same direction or at the same speed
- Any failure to achieve smooth motion of the body when walking on rough terrain.

In the energy saving methods of design, there are three basic principles employed (Todd, 1985):

- Minimize the dissipative losses (inefficiency of power transmission, environmental resistance)
- Minimize the energy conversion into unproductive forms by:
  - minimization of kinetic energy of the limbs by reducing their masses (e.g. fixing the heavy actuators to the body) and using the leg cycles which minimize acceleration
  - balancing of one limb movement against another (it effects in minimization of the disturbances of the body movement)
- Optimization of the legs and body relative proportions; proper legs and body design some arrangements are energetically favourable, minimizing accelerations or the masses of the reciprocating parts.

A detailed analysis of energy consumption using only modelling and simulation is not possible. It is not possible to include in the models all sources of energy dissipation and overestimation or underestimation of such sources may give a totally wrong effect. Therefore it is safe to use a simplified approach to the modelling which includes only most important factors which affect energy dissipation. The accuracy of such a simplification can be estimated using the knowlegde of the real device properties and observations of the power consumption in the existing walking machines.

2. Related research

Many works devoted to the energy problems of locomotion consider the total kinetic and potential energy of multi-legged walking machines. Energy losses in the approach are calcutated assuming that energy is mainly consumed to support the body weight, and to change potential energy due a change of the body centre of gravity altitude (if such an oscillation exisist for the assumed gait pattern), and by geometric work (cf Nagy et al., 1994; Shin and Streit, 1993; Lapshin, 1990; Naua and Waldron, 1995; Yeh-Sun Hing et al., 1999). Very often the specific resistance measure, first applied to walking machines by K.J. Waldron (cf Song and Waldron, 1986), is used for a comparative study of legged robots efficiency, e.g. Makoto Kaneko et al. (1987). The coordinate system showing specific resistance related to the average speed is known as the Gabriele-von Karman diagram (cf Gabriele and Karman, 1950).

This approach is helpful in the choice of leg link proportions (Ben-Sheng Lin and Shin-Min Song, 1993) since the specific resistance depends on the leg stride which is related to the leg length and link proportions. Using the approach it is easy to express the total energy consumption versus motion velocity or body height (body and legs motion is approximated by a simple inverted pendulum behavior) and it is usefull for analysis of different gait efficiencies, see Naua and Waldron (1995). But that approach is not practical in the design of the actuating part when the leg structure and gait type (cf Shaoping Bai et al., 1999; Zielińska, 1999) are given.

The motor power must be choosen in such a way that the machine will not be under- or over-powered. In multi-legged walking machines the conflict between the demand of weight minimisation, which also means application of small power motors and the expected motion speed is very serious. Utilisation of lighter motors results in greater gear reduction ratios which finally give a low locomotion speed. The existing walking machines move at a velocity of $0.5 \div 0.7\,\mathrm{km/h}$. A good selection of motor power, and gear ratio, as well as proper design of leg configuration is very critical as it can result in a greater speed and lower energy consumption. The designer of a walking machine should know what will be the range of consumed power of the chosen motors in relationship to the motion speed and machine weight – as that data dermines the choice of batteries, which in a fully autonomous walking machine must by carried on its back.

In this paper the results of energy efficiency analysis of the currently built walking machine (Zielińska and Goh, 1999) are presented. Attention is paid to calculations of motor powers, gear ratios and to the choice of energetically efficient leg configuration. The motor power is evaluated using the knowledge about the range of reaction forces during the hexapod movement, assuming that the body moves at a constant velocity, maintaining the height of the centre of gravity above the ground what is expected of hexapods.

3. Task specification

3.1. Direct and inverse kinematics problems

A six legged walking machine dedicated to the environment exploration is considered (Zielińska and Goh, 1999). The leg kinematic structure is given. To solve the direct and inverse kinematics problems (for the leg) the well known Denavit-Hartenberg approach is taken. The coordinate systems and local transformations are defined according to this formalism – Fig.1.

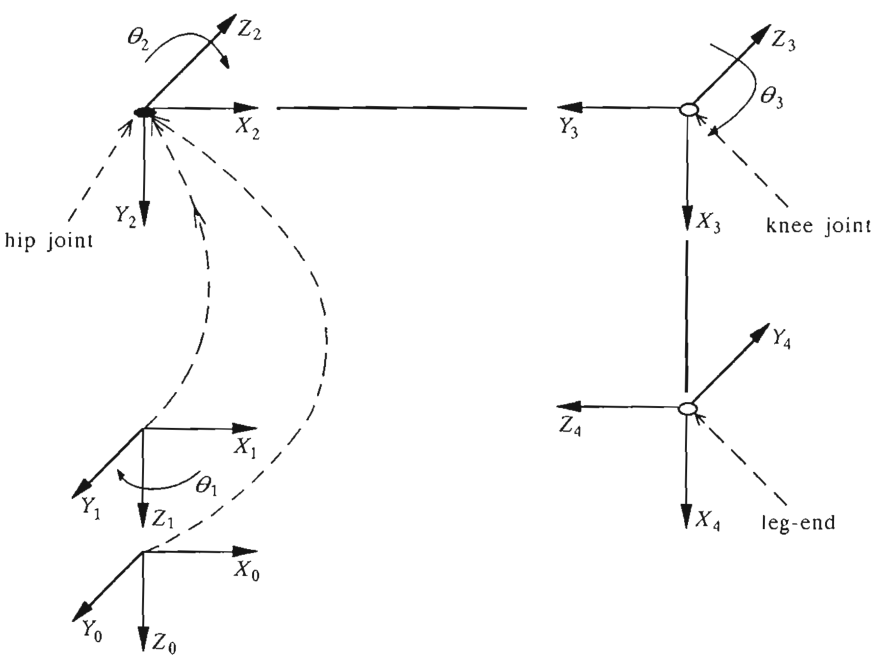

Fig. 1. Definitions of coordinate frame; l_1 – link length (distance from the hip to the knee joint), l_2 – link length (distance from the knee to the leg-end)

The four coordinate systems are defined, first – the base frame (immobile) is fixed to the hip joint $X_0Y_0Z_0$, next two frames $X_2Y_2Z_2$ (left-right rotation θ_1) and $X_2Y_2Z_2$ (up-down rotation θ_2) are moving frames with the origins locaded also in the hip joint.

The third frame $X_3Y_3Z_3$ has the origin in the knee joint and is rotating as the knee DOF — θ_3 does. The last frame is affixed to the leg-end - $X_4Y_4Z_4$ and moves together with the leg.

The Denavit-Hartenberg frame transformation parameters:

Frame No.	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	90°	0	0	θ_2
3	0	l_1	0	θ_3
4	0	l_2	0	0

Homogeneous transformation matrixes

$$
{}^0_1\mathbf{T} = \begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

where $s_i = \sin\theta_i$ and $c_i = \cos\theta_i$ and $s_{ij} = \sin(\theta_i + \theta_j)$, etc.

$$
{}^1_2\mathbf{T} = \begin{bmatrix} c_2 & -s_2 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s_2 & c_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad {}^2_3\mathbf{T} = \begin{bmatrix} c_3 & -s_3 & 0 & l_1 \\ s_3 & c_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^3_4\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & l_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Transformation matrix from frame 4 to frame 0 is equal to

$$
{}^0_4\mathbf{T} = {}^0_1\mathbf{T}\, {}^1_2\mathbf{T}\, {}^2_3\mathbf{T}\, {}^3_4\mathbf{T} \tag{3.1}
$$

The above multiplication yeilds the homogeneous matrix giving the Cartesian coordinates of the leg-end and its orientation. The Cartesian coordinates of leg-end expressed in the base frame are equal to

$$
\begin{aligned} p_x &= c_1c_2l_1 + l_2c_1c_{23} \\ p_y &= s_1c_2l_1 + l_2s_1c_{23} \\ p_z &= s_2l_1 + l_2s_{23} \end{aligned} \tag{3.2}
$$

The homogeneous matrix also shows the orientation of last frame relative to the base frame. The versors of the leg-end frame expressed in the base frame are

$$\boldsymbol{u}_x = \begin{bmatrix} c_1c_2c_3 - c_1s_2s_3 \\ s_1c_2c_3 - s_1s_2s_3 \\ s_2c_3 + c_2s_3 \end{bmatrix} \qquad \boldsymbol{u}_z = \begin{bmatrix} s_1 \\ -c_1 \\ 0 \end{bmatrix}$$

$$\boldsymbol{u}_y = \begin{bmatrix} -c_1c_2s_3 - c_1s_2c_3 \\ -s_1c_2s_3 - s_1s_2c_3 \\ 0 \end{bmatrix}$$

As each leg has 3DOFs only, the position of the leg-end in the Cartesian system can be controlled (not the orientation).

The inverse kinematics problem is solved using an algebraic approach (vs. geometrical). Dividing p_y by p_x using Eqs $(3.2)_{1,2}$ we have

$$\theta_1 = \arctan 2(p_y, p_x) \tag{3.3}$$

In the program, singular (degenerate) case when $p_x = 0$ was considered.

Using Eqs $(3.2)_{1,3}$ we obtain the formula for c_3

$$c_3 = \frac{(\frac{p_x}{c_1})^2 + p_z^2 - l_1^2 - l_2^2}{2l_1l_2} \tag{3.4}$$

For the result from the range of 0, 180° or 0, −180° is convienient to express θ_3 by the inverse tangent function using $s_3 = \pm\sqrt{1-c_3^2}$

$$\theta_3 = \arctan 2(\pm s_3, c_3) \tag{3.5}$$

Choice of the sign of s_3 is made by inserting the leg configuration (eg. insect type, reptile type). Constant positive sign is for insect and reptile like configuration.

To find θ_2 let $A = c_3l_2 + l_1$, then Eqs $(3.2)_{2,3}$ can be rewritten as

$$\begin{aligned} p_y &= s_1c_2A - l_2s_1s_1s_3 \\ p_z &= s_2A + c_2s_3l_2 \end{aligned} \tag{3.6}$$

We evaluate s_2 from Eq $(3.2)_3$ and substitute it into Eq $(3.2)_2$

$$p_y = C - Ds_2 - s_2B \tag{3.7}$$

where

$$C = s_1 A \frac{p_z}{s_3 l_2} \qquad D = \frac{s_1 A^2}{s_3 l_2} \qquad B = s_1 s_3 l_2$$

From Eq (3.7) we have

$$s_2 = \frac{C - p_y}{D + B} \tag{3.8}$$

From Eq $(3.2)_1$ we can evaluate c_2

$$c_2 = \frac{p_x + c_1 s_2 s_3 l_2}{c_1 A} \tag{3.9}$$

Eq (3.8) can be substituting into Eq (3.9) for unknown value of s_2, θ_2 can be found using the inverse tangent function $\theta_2 = \arctan 2(\pm s_2, c_2)$.

For the degenerate solution, when $\theta_1 = 0$ (when the absolute value of p_y is close to zero), the simpler relations are used

$$a = l_1 + l_2 c_3 \qquad b = l_1 s_3 \tag{3.10}$$

and finally

$$\theta_2 = \arctan 2(p_z, p_x) - \arctan 2(b, a) \tag{3.11}$$

3.2. Motion conditions and motor power calculation

We shall consider the planar motion of the six legged walking machinde over a horizontal surface. The machine body moves parallely to the support surface with a constant velocity v. The kinematic structure of the legs is given (every leg has the same structure), but the link lengths, as well the size of the body are parametrized and their influence on energy consumption is analysed. Leg joints are revolute, and are powered by motors connected to the mechanical system by means of gears. Reptilian or insect like leg configurations (Todd, 1985) are analised.

The notation is as follows:

l_1, l_2	–	lengths of the leg links: thigh and shank, respectively, [m]
v	–	motion velocity, [m/s]
M	–	total mass of the body (body and legs), [kg]
s	–	step length (which is defined as the distance covered by the leg-end relative to the body during the support phase), [m]
g	–	gravitational constant, [m/s^2]
r_i	–	reduction factor
t_s	–	support time (time of contact of the leg-end with the ground during one step), [s]
m_{max}	–	maximum economic motor speed, [rotations/s].

All legs perform the same periodic movement relative to the body. In calculation of the energy consumption of the walking machine we neglect the friction losses in the leg joints, limited efficiency of the actuating system, environment a resistance and soil deformation losses. The reduction factor r_i as is seen in the path from the joint to the motor is greater than one. Proportionally to this factor the torque at the output of motor is reduced in comparision to the torques which must be generated to actuate the movement of the machine. The joint speed in relation to the motor shaft speed is reduced proportionally to r_i (Kuo, 1998). A compromise between the speed (heigh speed – small value of r_i) and motors torque (small torque – higher value of r_i) is one of the design problems.

To calculate the torques in the leg joints during the support phase we use the Jacobian approach (Craig, 1986)

$$\boldsymbol{\tau} = \mathbf{J}(\theta)^{\top}\boldsymbol{F} \tag{3.12}$$

where

$\mathbf{J}(\theta)^{\top}$	–	transposed Jacobian matrix, [m]
$\boldsymbol{F}$	–	vector of the forces exerted by the leg to support and move the body. The components of the forces vector are equal to reaction forces but with opposite signs ($\boldsymbol{F} = [f_x, f_y, f_z]^{\top}$ [N]), Jacobian $\mathbf{J}(\theta)$ is expressed in the same frame as the force F (base frame $X_0Y_0Z_0$)
$\boldsymbol{\tau}$	–	vector of joint torques, [Nm]
τ_i	–	ith joint torque.

First the reduction factor r_i for the ith joint is calculated, for the assumed body speed v, step length s, link lengths l_1, l_2. In these calculations only the most energy consuming leg-end support phase (body movement propell in the support phase the total range of angle change in each joint $\Delta\theta_i$ for given leg posture, can be calculated. The support time t_s is equal to s/v.

The joint angular speed is equal to

$$\dot{\theta} = \frac{\Delta\theta_i}{t_s} \tag{3.13}$$

The maximum possible reduction factor (which minimises the motor torque requirement) is equal to the maximum economic motor speed (as given by catalogues) m_{max} divided by the joint speed

$$r_i = \frac{m_{max}}{\frac{\Delta\theta_i}{t_s 360^{\circ}}} \tag{3.14}$$

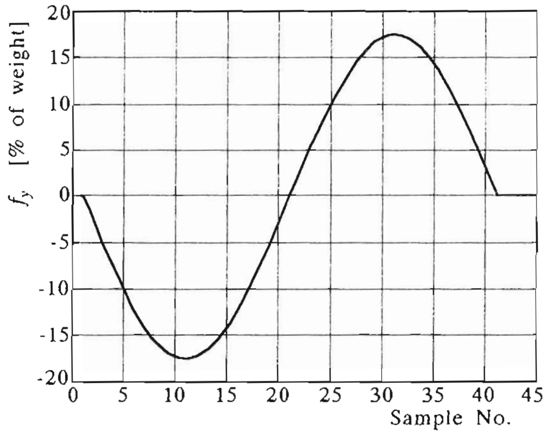

Fig. 2. Leg-end force component parallel to the direction of motion (along the Y axis of the base frame)

Knowing τ from Eq (3.12) we can calculate the motor torque τ_m, but the reaction forces must be known. In the presented analysis it was assumed that the vertical reaction forces were distributed evenly over the three supporting legs, and so $f_z = Mg/3$. A three leg support phase is typical the for most energy consumnig tripod gait. The horizontal force f_y exerted by the leg and directed along the vector of the motion of the machine is approximated by the shape shown in Fig.2 and the force component perpendicular to the motion direction was assumed to be constant and equal to $0.175Mg$. In this approximation the knowledge of reaction force distribution during insect locomotion (Pfeiffer, 1990) and the worst cases (extremum case) are taken into account. The motor torque τ_i^m which must be produced to actuate the ith joint movement is equal to

$$\tau_i^m = \frac{\tau_i}{r_i} \tag{3.15}$$

Assumnig that this torque will be produced permanently during the support phase and assuming that the motor speed will be permanently equal to m_{max} the expected motor power P_i can be approximated by

$$P_i = \tau_i^m m_{max} = \tau_i \frac{\Delta\theta_i}{t_s 360^\circ} \tag{3.16}$$

The presented method of motor torque and power calculation yeilds an overestimation. On the other hand we negtected the limited efficiency of the mechanical and actuating system, the motors efficiency is in range of 80%, and the efficiency of gearheads is 70% [6], friction and other sources of energy dissipation are also neglected.

4. Comparative study of energy efficiency

For the given leg kinematics the transposed Jacobian is equal to

$$\mathbf{J}^{\top} = \begin{bmatrix} -s_1c_2l_1 - s_1l_2c_{23} & c_1c_2l_1 + l_2c_1c_{23} & 0 \\ -c_1s_2l_1 - c_1l_2s_{23} & -s_1s_2l_1 - l_2s_1s_{23} & c_2l_1 + l_2c_{23} \\ -l_2c_1s_{23} & -l_2s_1s_{23} & l_2c_{23} \end{bmatrix}$$

During the support phase the p_z and p_x the coordinates are constant (p_z is related to the height of the body and p_x is "from side to side" leg-end translation in relation to the hip).

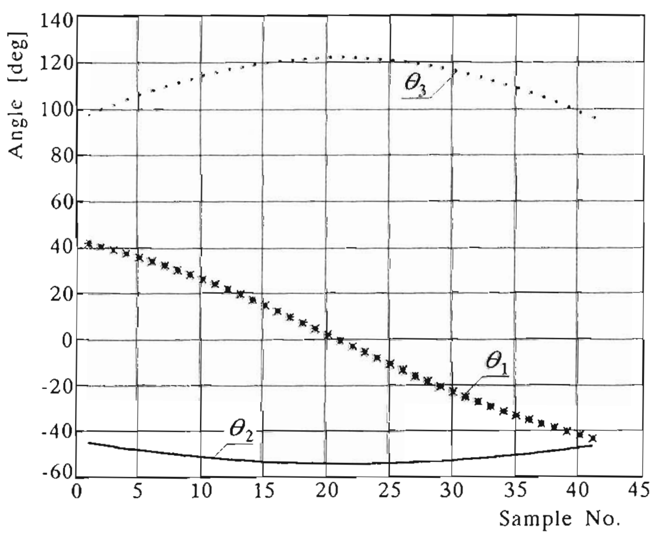

Fig. 3. Angle change in the support phase

Fig.3 is shows the change of joint angles during the support phase. For these angles the torques which must be produced in the hip joint (according to Eq (3.12)) were calculated (see Fig.4). Machine total mass was egual to 30 kg, and $l_1 = 0.3$, $l_2 = 0.4$, and the insect leg configuration was included (with $\theta_1 = 42°$, $\theta_2 = -45°$, $\theta_3 = 98°$ in the beginning of support phase and $\theta_1 = -42°$, $\theta_2 = -45°$, $\theta_3 = 98°$ on its end).

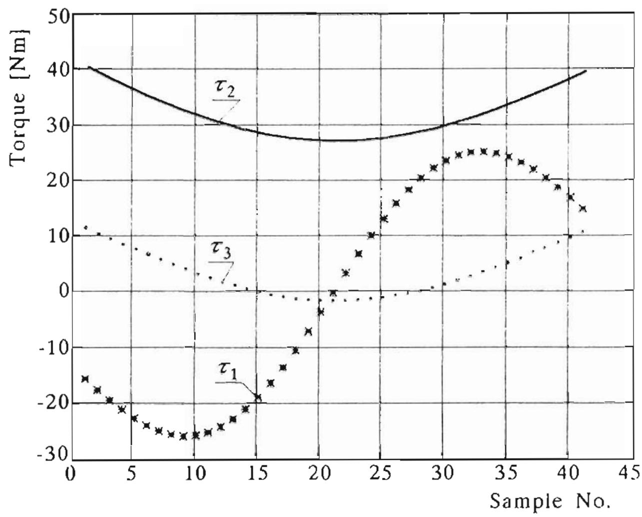

Fig. 4. Joint torques in the support phase

For the considered configuration θ_1 produces forward movement of the body and is changing symmericaly around zero, θ_2 and θ_3 are mostly "responsible" for elevation of the body and are changing in a narrow range (see Fig.3). The following configurations were considered (initial value):

Configuration 1: $\theta_1 = 42°$, $\theta_2 = -45°$, $\theta_3 = 98°$ (insect configuration)

Configuration 2: $\theta_1 = 42°$, $\theta_2 = 0°$, $\theta_3 = 90°$ (typical reptile configuration)

Configuration 3: $\theta_1 = 42°$, $\theta_2 = 10°$, $\theta_3 = 80°$ (reptile configuration)

Configuration 4: $\theta_1 = 42°$, $\theta_2 = -10°$, $\theta_3 = 92°$ (intermediate configuration: insect – reptile type)

Configuration 5: $\theta_1 = 42°$, $\theta_2 = -20°$, $\theta_3 = 94°$ (insect configuration)

Configuration 6: $\theta_1 = 42°$, $\theta_2 = 30°$, $\theta_3 = 50°$ (intermediate configuration: reptile – mammal type)

Configuration 7: $\theta_1 = 42°$, $\theta_2 = -30°$, $\theta_3 = 96°$ (insect configuration).

As it is shown in Fig.5, in many cases (i.e. configurations) a ratio lying l_1/l_2 within the range of 0.3 to 0.9 is associated with smaller motors power rather than that for other leg links proportions.

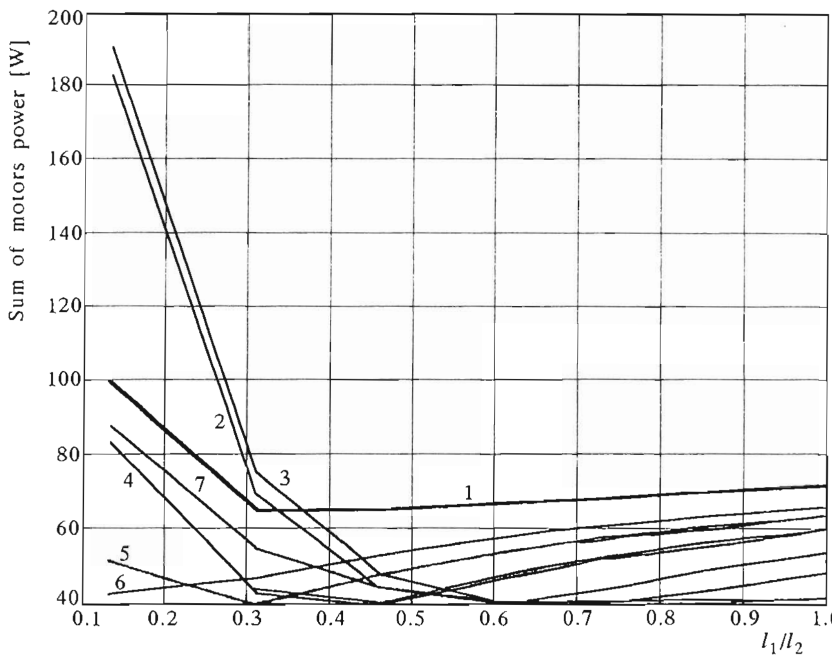

Fig. 5. Influence of leg configuration and proportion on the motor power (number of each curve specifies the configuration) – see text above

For all the cases considered, insect configuration 7 is optimal (low motors power requirements) for l_1/l_2 greater than 0.6. Such a low power require can be observed in other configurations only for exactly fixed l_1/l_2 proportions (e.g. for configuration 5 where $l_1/l_2 = 0.3$ or for configuration 4 where $l_1/l_2 = 0.48$).

For l_1/l_2 greater than 0.5 the configuration can double the power requirement. For example, for l_1/l_2 equal to 1 the power requirement depends noticeably on the configuration and is in the range of 40 to 80 W). On the other hand for the ratio smaller than 0.3 the range of power change in relation to configuration is much greater – e.g. 45 to 145 W for 0.2. Summarising for the designer, the ratio l_1/l_2 between $0.6 \div 0.8$ can be suggested as the optimum choice as for that ratio for all configurations motors power is mimimal or is not far from minimal demand.

The influence of linear speed of the machine and the total weight of the body on the expected motor power was also analysed. Selected results are shown in Fig.6 and Fig.7. In Fig.7 the least energy consuming configuration 7 was considered. For that configuration, the ratio l_1/l_2 was equal to 0.75,

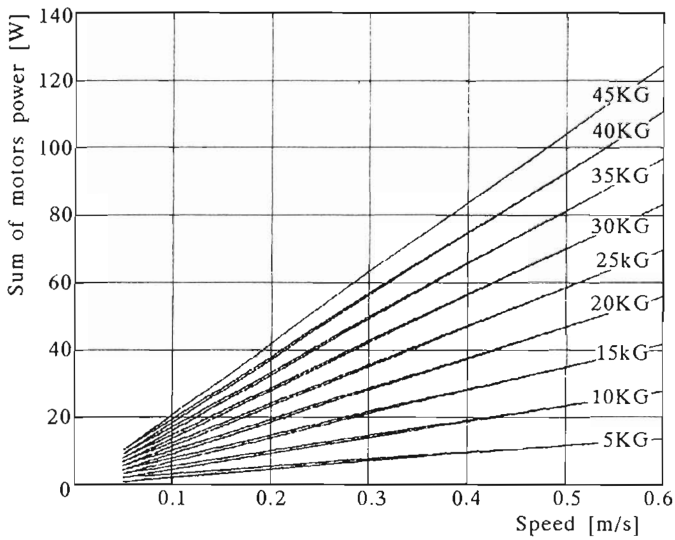

Fig. 6. Power requirements in relation to the weight and speed – configuration 1

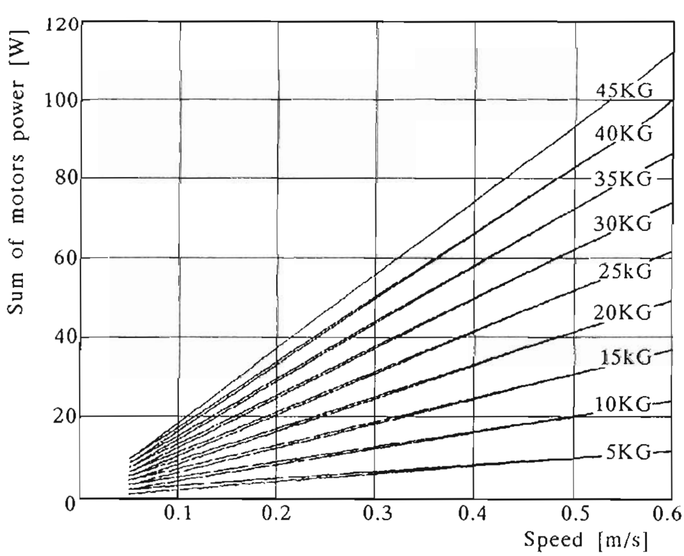

Fig. 7. Power requirements in relation to the weight and speed – configuration 7

which is in optimum range as was mentioned above.

From Fig.6 and Fig.7 it can be seen that an increase in speed or in weigth results in an increase in motors power, and for high speeds the expected motors power grows faster in relation to the weight than for lower speeds.

The conflict between expectation of hight speed and low energy consumption is easy to observe there.

5. Conclusions

The development and usability of walking machines can be constantly improved in terms of a proper design. The final goal of presented works is to develop small autonomous walking machine which will be optimal from the point of view of energy consumption and will be able to operate autonomously under natural conditions – see Fig.8.

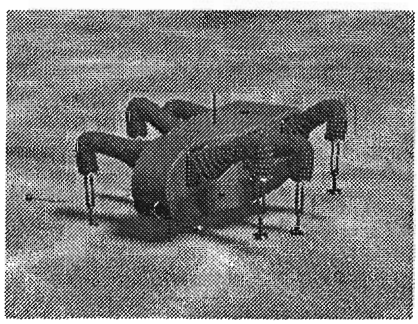

Fig. 8. View of a walking machine (by W.Czajewski)

The approach used for the motor design, and analysis of the relations between leg proportions, leg configuration, motion velocity and weight of the machine are shown.

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Analiza efektywności w projektowaniu maszyn kroczących

Streszczenie

W artykule przedstawiono problem efektywności energetycznej, jaki musi być uwzględniony przy projektowaniu maszyny kroczącej. Uwagę poświęcono zagadnieniu doboru mocy silników, doboru przekładni oraz wyborowi energetycznie efektywnej konfiguracji nóg. Moc silnków została wyznaczona na podstawie znajomości rozkładu sił reakcji w czasie chodu maszyny kroczącej, przy ruchu ze stałą prędkością i przy stałej wysokości środka ciężkości maszyny nad podłożem. Przyjęte założenia są typowe dla chodu maszyn sześcionożnych. Omówione wyniki zostały zastosowane przy projektowaniu aktualnie budowanej maszyny kroczącej.

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