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Autonomous walking machines – discussion of the prototyping problems

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Abstract. An improvement of the computer technology caused the progress in building of the developed machines, indispensable in some works which are too dangerous or onerous for humans. The article deals with prototyping problems in constructing autonomous walking machines including design problems, evaluation of required motor power, evaluation of expecting walking velocity as well as the control system design considerations etc., presenting themselves as key factors which must be taken into account while walking robots prototyping.

Key words: autonomous walking machines, prototyping problems.

1. Introduction

The development and the usability of the developed machines has been constantly improved, aided by the improvements in the computer technology. There have been many publications underlying that legged locomotion is the best form of locomotion through varying terrain, as compared to using wheels. The surface of a terrain may be uneven, soft, muddy and generally unstructured. Legs in the biological environment demonstrate significant advantage in such situations. Legged robots can aid in applications that require searching on unstructured environments for hidden or buried materials (e.g. crash recovery), hazardous objects (e.g. mines or bombs). The multi-legged walking machines imitating usually by their structure the living creatures (as insects) stimulating the researchers to study a natural gait properties and to adapt results of biologists' observations to technical devices. Many new walking machines projects are performed together with the biologists; and technicians cooperation [1, 2]. Statically stable walking machines are very promising devices for pick and place operations of objects in natural conditions. As an example of such utilization it can be given the picking and transporting of small dangerous materials (radioactive, firing materials). Machine used for such task can be controlled from the distance by the operator using the radio-link connection and joystick. Walking machines are also the excellent testing rigs to develop sophisticated control algorithm (e.g. different force control methods), and to test the new methods of motion planning.

2. Design problems

Designers of legged machines must take several decisions which influence the technical features of these systems. As the most important of these one can list: – the mechanical structure and leg configuration (choice of number of legs, their kinematics structure, – joint design solution), – actuating and drive mechanisms (choice of motors type, evaluation of their power, – design of motor placement and evaluation of methods of motion transmission from motors to the legs joints), – evaluation of expected power consumption in relation to the machine's weight, payload, – motion conditions (soft, hard terrain, inclined terrain, etc.) and assumed method of walk (speed of motion, number of legs supporting the body during walk, etc.). An important consideration is the adequate specification of the control system (on board/of board control system, control software, hardware and software control systems architecture, distribution of the on board utilities, cables, sensors which influences the stability conditions, etc.). Machines autonomy depends on the internal sensors delivering the information about the internal state of the device and on the external sensors detecting the external environmental conditions. These information must be properly used by the control software which finally determines the machine's "intelligence".

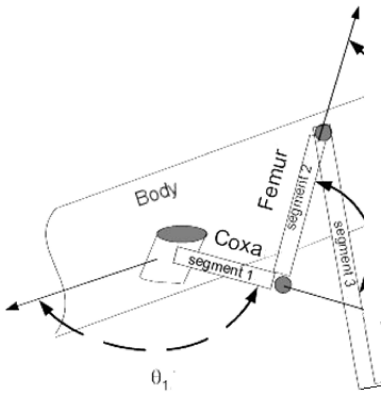

Fig. 1. Figure shows the basic insect leg configuration. This configuration is typically used for average size machine (i.e. 20 kG weight, 0.6 m body length, 0.5 m body width). It offers the big supporting area

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Several basic configurations exist for walking machines that have been developed so far.

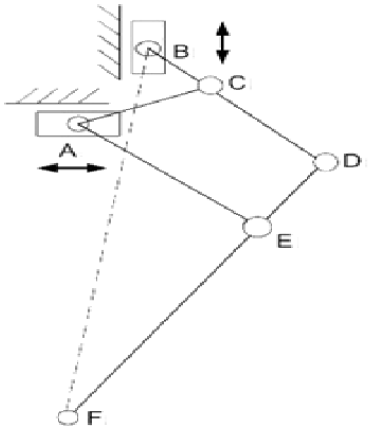

Fig. 2. Figure shows the pantograph leg configuration of leg design. The points at A and B move linearly (usually driven by a lead screw motor). If the mechanical linkage is designed carefully point F can closely follow the straight line during the support phase

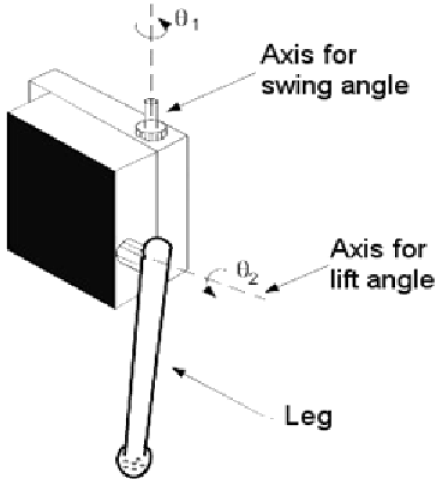

Fig. 3. Figure shows a leg configuration that is commonly used in a variety of light, small legged robots. This design employs two servo motors attached back to back. Each motor is responsible for either the lift or swing motions. This solution allows the machine to be invertible

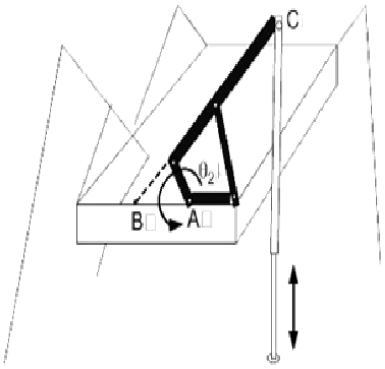

Fig. 4. Figure shows a hybrid leg design using the pantograph structure with linear actuators generating leg lift (actuator located the leg segment) and swing (actuator attached to point B)

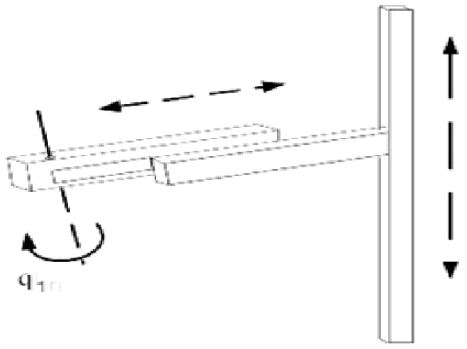

Fig. 5. Figure shows a 3 DOF leg design which employs linear actuators for the leg lift and leg side motion, the revolute actuator produces the leg swing

In the above designs, individual motors are responsible for individual (or single) actuation of the leg joints. Our team proposed the novel mechanical solution were collective motor actuation was employed. This idea utilizes the effort of 2 motors to cooperatively control leg lift and swing movement. Two motors are located in the hip section and third one is in the knee section. The hip motors work collectively to generate combined leg swing and lift. This solution offers a large work space of the leg, allows easy change of its posture and decreases the leg weight. Individual lift and swing angles beyond $180°$ thus providing the vehicle with a high degree of motion dexterity to perform a variety of configurations beyond the basic walking and support functions. Each of the other above illustrated designs has serious postural and workspace limits. This design was applied in small quadruped LAVA and in the bigger hexapods GROVEN (4 such robots have been built till now).

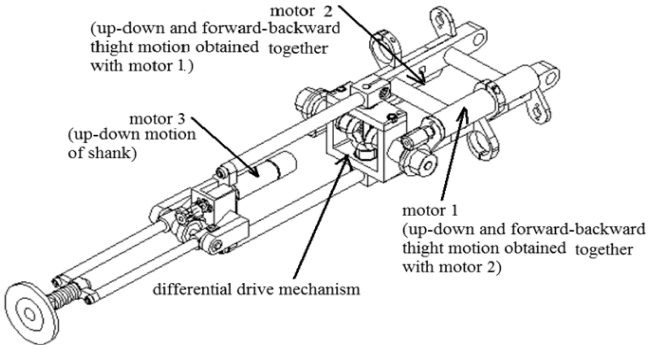

Fig. 6. Leg design – novel proposition (author J. Heng, control and improvements T. Zielinska)

3. Energy efficiency

Mechanical efficiency of locomotion of the existing walking machines is very low in comparison to the living animals and low in comparison to 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 [3]. The designer of a walking machine must analyze of the energy consumption which determines the choice of mechanical structure, and the propulsion and powering systems. For the design of small,

light quadruped LAVA the choice of proper motors was not so critical as the motors design for much bigger hexapods dedicated for the motion in natural environment. Due to the power supplies limits (batteries were carried on-board) and expected high payload of those machines the careful motors choice without increasing the machines weight over the needs was required.

The sources of energy dissipation in legged locomotion are as follows [1]:

1) loss of energy which must be applied to the whole machine to make a leap,
2) loss of kinetic energy which must be applied to the limbs to make them oscillate,
3) soil adhesion to leg-ends, and other forms of motion resistance,
4) power wasted in supporting the body against gravity and other forces,
5) 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 geometric work), inefficiency of actuators and power sources,
6) opposing actuators (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 energy saving methods of design, there are three basic principles [1]:

- minimize the dissipative losses (inefficiency of power transmission, environmental resistance),
- minimize the diversion of energy into unproductive forms by:
  a) minimization of kinetic energy of the limbs by reducing their mass (eg. fixing the heavy actuators to the body) and using of leg cycles which minimize acceleration,
  b) balancing of one limb movement against another it effects in the minimization of the disturbances of the body movement),
- optimization of the legs and body relative proportions concerning the dimensions (proper legs and body design); some arrangements are energetically favorable, minimizing accelerations or the mass of the reciprocating parts.

Detailed analysis of energy consumption which uses only modeling 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 a sources may give totally wrong effect. Therefore it is safe to use a simplified approach considering the modeling which includes only most important factors which influence energy dissipation. The accuracy of such simplification can be estimated using the knowledge of the real device properties and observations of the power consumption of the existing walking machines. To solve the direct and inverse kinematics problems (for leg) the well known Denavit-Hartenberg approach is applied. To design the motors power we consider the planar motion of the six legged walking machine over a horizontal surface. The machine's body moves parallel to the support surface with a constant velocity v. Every leg has the same structure, but the link lengths, as well the size of the body are parameters and their influence on the energy consumption is analyzed. Leg joints are rotational, and are powered by motors connected to the mechanical system by gears. In calculation of the energy consumption of the walking machine the following factors were first ignored: – the friction losses in the leg joints, – limited efficiency of the actuating system, – environment resistance and the soil deformation losses. The knowledge of reaction force distribution during insect locomotion [4, 5] and the worst case (extreme case) were taken into account. The presented method of motor torque and power calculation yields an overestimation. On the other hand, we neglected the limited efficiency of the mechanical and actuating system, the motors efficiency is in range of 80%, and efficiency of the gear heads is 70%, friction and other sources of energy dissipation are also neglected – as it was mentioned before.

4. Evaluation of required motors power

The energy efficiency study were applied to the currently build walking machine. Attention was paid to the calculation of motor powers and gear ratios. To achieve the required load bearing capacity the motors with a high torque-to-weight ratio must be applied. Additionally the gears with high reduction ratio and low weight are needed. In existing hexapod designs, motors and gears together contribute more than 50% to the total weight of a leg. The motor-gear combination in the joints requires detailed optimization with aim to achieve maximum load capacity. To simplify fabrication of parts and maintenance, the developed six-legged walking machine consisted of three identical, symmetric leg pairs.

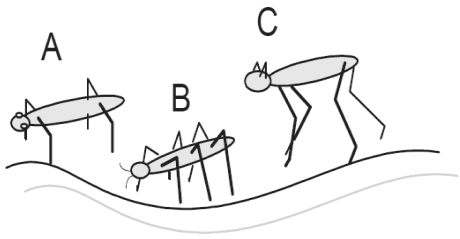

Fig. 7. Leg postures: A – mammalian, B – insect, B – reptile

The kinematics structure of the legs was given (every leg has the same structure), but the link lengths, as well the size of the body were parameterized and their influence on the energy consumption was analyzed. Leg joints are rotational, and are powered by motors connected to the mechanical system by gears. Different leg postures were analyzed (Fig. 7) to properly choose the needed motors. The notations are as follows:

- l_1, l_2 – the lengths of leg links; thigh and shank respectively,
- v – motion velocity [m/s],

- W – total weight of the body (mass of body and legs)[kG or N],
- s – the step length (which is defined as the distance covered by leg-end relative to the body during the support phase) [m],
- r_i – reduction ratio,
- t_s – support time (time of contact of leg-end with the ground during one step) [s],
- $m_{\max}$ – maximum economic motor speed [revolutions/minute] = [rpm] (note: [rpm] – revolution per minute is the unit used commonly by motor producers, for the readability and easier comparison with other motors, in this text is followed this convention).

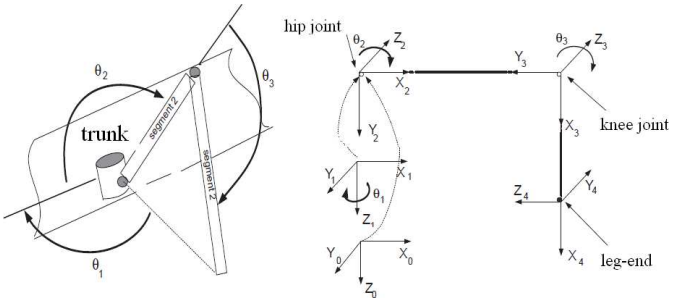

Fig. 8. Insect type leg posture and definition of coordinate frames

All legs perform the same periodic movement relative to the body. The reduction ratio r_i seen in the path from the joint to the motor is much bigger than 1. Proportionally to this ratio the torque at the output of motor is reduced in comparison to the torque which is produced to actuate the movement of the machine. The joint speed in relation to the motor shaft speed is reduced proportionally to r_i. Compromise between the speed (high speed – small value of r_i) and motors torque (low torque – higher value of r_i) is one of the design problems. To calculate the torque in the leg joints during the support phase the Jacobian approach was applied:

$$\tau = \mathbf{J}^T(\theta)\mathbf{F}, \tag{1}$$

where $J^T(\theta)$ is the transposed Jacobian matrix; F represents the force vector (in base frame - X_0, Y_0, Z_0), exerted by the leg to support and move the body. The components of the force vector are equal to reaction forces, but with opposite signs: $\mathbf{F} = [f_x, f_y, f_z]^T$ [N], τ is the vector of joint torques[Nm]; τ_i is the ith joint torque. The direct and inverse kinematics problem was solved for the legs with Denavit-Hartenberg coordinate frames definition. As one leg has only 3DOF, solution of the inverse kinematics problem was less complicated and for that the algebraic approach was applied. In Fig. 8, the definition of the coordinate frame is illustrated. In this figure, the frame X_0, Y_0, Z_0 is the frame attached to the body. This frame is non-moving (base frame – with reference to the leg motion). Frame X_1, Y_1, Z_1 and X_2, Y_2, Z_2 are moving frames attached to the hip joint (2 DOF). Frame X_3, Y_3, Z_3 is attached to the knee, and frame X_4, Y_4, Z_4 has origin connected to leg-end. The leg-end coordinates expressed in frame X_0, Y_0, Z_0 are:

$$\begin{aligned} {}^0x &= l_1\cos(\theta_1)\cos(\theta_2) + l_2\cos(\theta_1)\cos(\theta_2+\theta_3),\\ {}^0y &= l_1\sin(\theta_1)\cos(\theta_2) + l_2\sin(\theta_1)\cos(\theta_2+\theta_3),\\ {}^0z &= l_1\sin(\theta_2) + l_2\sin(\theta_2+\theta_3). \end{aligned} \tag{2}$$

For the assumed body velocity v, step length s, and link lengths l_1, l_2 using (2) the Jacobian matrix was evaluated and basis on (1) the maximum and average joint torque was calculated. In these calculations, only the most energy consuming, leg-end support phase (body movement propelling phase), was considered. The total range of angle change in each joint for given leg posture was taken into account. The support time t_s for walk with constant velocity is equal to s/v. In the presented results (evaluation of torque demand using Jacobian approach) the values of reaction forces were taken from experimental data. They were measurements of reaction forces obtained for insect locomotion increased by the ratio resulting from the machine and insect total weight proportion [4, 5]. The typical for six-legged walking machines range of joint angles has been considered (that means also the typical step length for given size of the machine). The most representative shape (time history) of reaction forces was considered for calculation of average torque demand.

4.1. Assumptions. Forward motion by tripod gait, total weight of robot: $W = 40.000$ [kG] (392.400 [N]), length of leg links: $l_1 = 0.320$ [m] (segment 1 – thigh), $l_2 = 0.400$ [m] (segment 2 – shank), leg reaction forces (average): f_z(vertical)= 130.800 [N], f_y (along motion direction)= 68.670 [N], f_x (side component of force vector)= 68.670 [N], angles on the beginning of support phase: $\theta_1 = -45.0°$, $\theta_2 = -30.0°$, $\theta_3 = -15.0°$, total range of angles change (in support phase): $\Delta\theta_1 = 90.0°$, $\Delta\theta_2 = 20.0°$, $\Delta\theta_3 = 50.0°$.

4.2. Evaluation of torque demand. The leg is most loaded in its support phase, considering the tripod gait (in every moment of time robot body is supported by three legs) and relation (1) the values of joint torques during support phase where calculated. It was identified that the maximum torque in hip joint is 121.938 [Nm], this torque is needed to support the robot when leg-end (each of three supporting legs) is in position: ${}^0x = 0.396$ [m], ${}^0y = -0.396$ [m], ${}^0z = -0.443$ [m] (see Fig. 8 for the orientation of the reference frame X_0, Y_0, Z_0, maximum knee torque = 63.404 [Nm] is for leg-end position equal to ${}^0x = 0.396$ [m], ${}^0y = -0.198$ [m], ${}^0z = -0.443$ [m]. Having the time courses of the torques over the support phase the absolute values of average required torques were calculated; in the hip it is – 111.900 [Nm], and in the knee – 42.620 [Nm]. Other important data are – leg-end coordinate in beginning of support phase: ${}^0x = 0.396$ [m], ${}^0y = -0.396$ [m], ${}^0z = -0.443$ [m], – hip torque (abs.) in the beginning of support phase = 127.625 [Nm], and knee torque (abs) in the beginning of support phase = 64.464 [Nm].

4.3. Calculation of motors power (and reduction ratio) for demanded walking speed. The demanded linear speed of the walking machine was 0.5m/sec, for typical leg stepping the total amount of angle change in hip joint was equal to $\Delta\theta_1 + \Delta\theta_2 = 92.195°$, length of step – $s = 0.792$ [m], time to perform one step – $t_s = 1.584$ [s], this gives the needed angular velocity – $\dot{\theta}_{1,2} = 58.21$ [°/s], $\Delta\theta_3 = 50.0°$ and $\dot{\theta}_3 = 31.569$ [°/s]. For the average motor the revolute speed is not greater than $m_{\max} = 5000.00$ [rpm]. Taking into account evaluated angular velocity, the required revolute velocity in hip joint is 9.702 [rpm] and required revolute velocity in knee joint is 5.261 [rpm]. From this velocity requirement the reduction ratios of the reducers mounted on the motor shafts were evaluated: hip reduction – $5000/9.702 = r_{12} = 515.374$, knee reduction – $5000/5.261 = r_3 = 950.302$. With this reduction the torque τ_{1+2} which must be delivered by motors to hip joint was evaluated $\tau_{1+2} = 111.900$ [Nm]/515.374=0.21712 [Nm]. This is for two motors for powering hip joint, therefore the torque needed from each motor is $\tau_{12}/2 = 0.21712$ [Nm]/2 = 0.10856 [Nm]. For knee joint motor it was obtained $\tau_3 = 42.620$ [Nm]/950.302 = 0.04485 [Nm]. Power of each hip motor must be 56.843 [W], and the knee motor power 23.483 [W]. It can be noticed that the required power of each hip motor is close to 60 [W]. From the chosen manufacturers catalogue, the offered motors had power 45 [W], 75 [W], or 90 [W]. Tho select 45 W motors was too less, while parameters of 75 W motors (voltage, current, weight, etc.) were very close to the parameters of 9 [W] motors. The weight and size of the 45 [W], 70 [W] and 90 [W] motors were the same. With a view to provide the option of increasing the walking speed of the machine with added torque, the 90 [W] motors were chosen in this design step for both hip and knee joints.

A 90 [W] motor mass is about 1 kg, and that includes the encoder and planetary gearbox for reduction purposes. In a single leg, three motors (2 for the thigh and 1 for the knee) are required to provide sufficient torque for the leg to propel the body forward. With the mechanical structure included, a single leg could weight up to 6 kG. Six legs of this same configuration will have a total weight of 36 kG. The weight of the robot including the electronics watertight body and sensors was estimated to be at 60 kG. Besides weight, other limitations such as current drain for each motor (2 A) as well as a high surge current of 24 A over 5ms to start all the motors during power up of the robot. An earlier intent of using dry-cell batteries to provide power to for autonomous operation not meet the power requirement necessary to satisfy these critical conditions. An alternative of using wet cells that would be able to satisfy the minimum surge current requirement was applied. However, the weight for the wet cells is 24 kG and that further increased the total weight of the robot to 84 kG. With this increase in weight, the original desired walking speed of the robot would thus be significantly reduced. Efforts were then devoted to reduce the weight of the machine by trimming off unnecessary weight. Instead of using metal parts or components, light weight materials such as plastic or tubular materials were introduced. Still, no significant reduction in weight was achieved.

Due the this problem another approach was taken: estimate the power ratings of the motor by fixing the weight of the walking machine and the ratings of the motor required. The weight of the machine was now assumed to be around 36kG, with similar leg link lengths as that provided in the earlier calculations. With this is mind, the final results were achieved.

4.4. Evaluation of expected walking velocity when minimizing applied motors power. In the next stage of motors choice it was assumed that the motors with lower power will be applied what will limit the walking speed. Considered in that stage motors power was 20 [W]. The power delivered in the hip joint was equal to 2×20 [W], and in the knee was 1×20 [W]. Torque delivered by those motors (according to catalogue) was following; in hip joint (for 1 motor) – 0.03820 [Nm], and the same was in the knee joint – 0.03820 [Nm]. Reduction ratios were calculated using the results for delivered and needed torque. When the walking speed is not the design demand the reduction ratio results from the proportion between delivered and needed torque. The needed torques are given in subsection *Evaluation of torque demand.*.). The reduction for hip motors was 0.5×111.900 [Nm]/0.03820 [Nm] = 1454, and knee reduction 42.620 [Nm]/= 1115.0. The resultant joint speed resulted from the motor speed divided by reduction ratio. Taking into account the motor velocity 5000 [rpm] (from catalogue) resultant hip velocity was 5000 [rpm]/1454=3.44 [rpm]. For the knee it was 5000 [rpm]/1115= 4.484 [rpm]. From there the achievable walking speed was $v = 0.195$ [m/s]. Time of one step is $t_s = 4.051$ [s] and $\dot{\theta}_{1,2}$ – 22.757 [°/s], $\dot{\theta}_4$ – 29.874 [°/s].

With this last scheme of the motors choice the machine weight must be kept around 36kG because only that weight can be supported by three legs in tripod gait when 20 [W] motors are applied.

4.5. Discussion. To quantify these results, it should be noted that in the evaluation of torque demand it must be added the significant margin (in order to deal with different energy losses and for emergency purposes). In average this factor is not less than 40%. In presented calculations of the motor power the ideal efficiency of the mechanical system was assumed. The energy (forces, torque) losses over the mechanical construction are normally rated at about 50–60%. On the other hand given in catalogues average motor torques can be exceeded for the short time by about 30% what can cover the part of energy shortage in emergent situation. This is permissible only when the motors are overloaded temporarily but not continuously. When the leg is in the transfer phase the motors are loaded very little comparing the support phase. Therefore in some sense (when due to the limits of power supply and robot weight constraints the design must be "tailored") the energy losses in the design phase can be neglected to some extend. If it is expected that the motors will be loaded continuously the calculated demanded torque must be increased by 40% up to 60% .

Utilizing the above results 3 prototypes were build. In first one the motors with lower power were applied, taking into account the need of energy losses cover the final robot weight was kept up to 32 kG (not 36 kG as considered in calculations). In 2 other robots were used the motors with greater power. Application of greater power resulted not only in greater walking speed but also in some additional payload of the robots. Those robots weighted 45 kG each. The successful testing in natural conditions confirmed the presented method of motors evaluation.

5. Force control

5.1. Introduction. Implementation of force control algorithm allows to follow the given (reference) force during the support phase, such forces pattern must be produced using the forces and torques equilibrium conditions [6, 7].

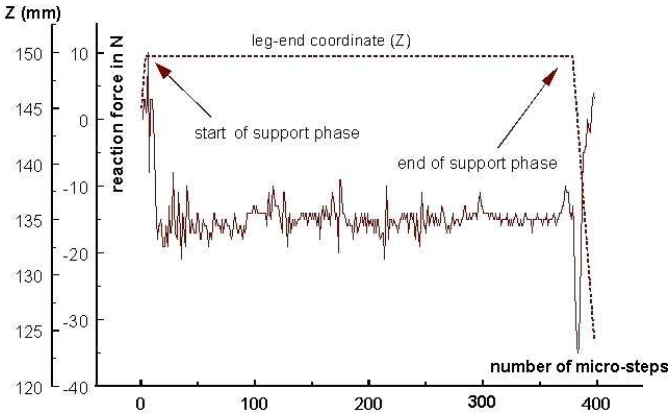

Fig. 9. Reaction force during support phase (without force control)

Force control raises the adaptability of the machine to irregular terrain and on different types of soil. In locomotion over a complex terrain, the necessity to control the horizontal force components, so that contact forces are within friction cones may arise. In locomotion on soft soil, it is necessary to control the leg loads because of their sinking into the soil. In locomotion over slightly uneven terrain, the leg sinking can be determined taking into account leg joints position, readings from inclinometers and loading on the legs read from leg-end force sensors. For loose sandy loam the sinking is irreversible. Such soil behaves as an absolutely rigid support if the load on the foot becomes less than the maximum value already achieved. Force controlled walking machine would give additional advantages by increasing energy efficiency by the reduction in internal forces between legs and providing the desired support forces regardless of the behavior of the terrain walked on. Low adaptability to the environment is the problem of position control. A position-controlled leg of walking machine would either move in the air without producing any forces for the body or exert all the forces available in the case of an uneven terrain. The latter possibility happens if there is a position error (due the lack of proper environment model, due to the control method or due to the change of environment properties.

5.2. Implementation of compliance force control. The force measurement is performed once for one control step. Control step consist of several micro-steps which are used to produce corrective control signals to obtain the real value (in our case it is leg-end force and leg-end position) to be close enough to the reference value. During each micro-steps the leg-end position is corrected according to the force compliance control law.

Control step – is the time period for which one reference value from higher-level control layer is applied. During this control step several micro steps are realized to achieve the reference value. For the leg-end position/force control the following relation was implemented [8]:

$$\Delta z_{i+1} = (z_{ref} - z_i)k_p \; + \; (f_{ref} - f_i)k_f, \qquad (3)$$

where z_i, z_{i+1} – are the vertical leg-end coordinates (in the frame connected to the hip and non-moving in relation to the body), z_i is the reference value for previous micro-step, z_{i+1} – for the actual micro-step, z_{ref} – is the constant reference value giving the expected vertical leg-end position during the support phase, f_{ref} – is the reference force, constant for the whole support phase, f_i – is the vertical force measured in previous control step, k_p, k_f – are proportional gains. It is easy to notice that the factor k_p depends on how fast the leg tends to come back to z_{ref} after force impulse. Factor k_f gives the leg-end force sensitivity. k_f to k_p ratio decides for what leg is more sensitive (for force error or for position error).

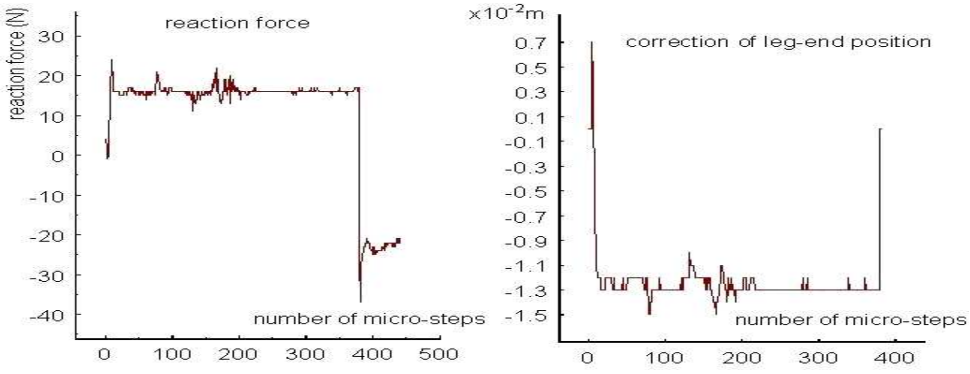

Fig. 10. Reaction force (left) and leg-end position with force control

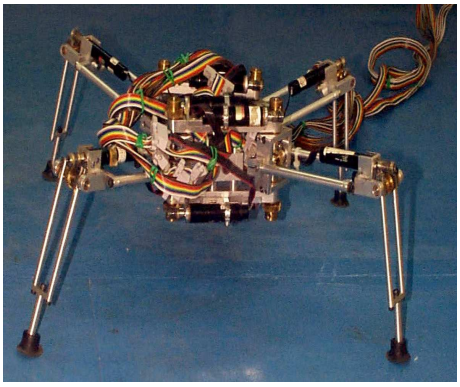

Fig. 11. Quadruped LAVA

In practical implementation, this relationship was supplemented by logic rules for filtering the force measurements noises and for limiting the maximum leg-end displacement during one micro-step. The force sensor set provided the analog filtering of high frequency noises. The additional logic rule was introduced to reject the wrong force measurements exceeding the machine weight (this wrong result was rarely possible due to the electric noises). Another logic rule was applied to switch on the force control only during leg-end landing and support phase. During the take off and leg-end transfer phase the force control was off. Next rule prevented of extreme leg elongation limiting the leg-end position in landing and support phases limiting the leg extension to the certain value determined by the expected nominal height of the machine and the leg-end work space. Bigger value of k_f results on bigger leg sensitivity to the sensed forces what can produce the continuous leg vibration. For this compliance force control during the landing and support phase the k_f equal to 0.08 and k_p equal to 0.25 were used. Time course of vertical component of reaction force during the leg-end support phase without force control shows Fig. 9. Figure 10 illustrates the reaction force and leg-end position correction during force compliance control applied in small walking machine with weight equal to 2 kG (Fig. 11). The details of LAVA control system and its realization issues are given in [10].

6. Control system

The advantage of hexapods are simple control rules (i.e. stability, terrain adaptation). One of the currently considered issues regard the problem of the optimum multi-processor control [4, 5]. Work is focused on the design of hardware structure as well the software functional decomposition. The real time QNX operating system with real-time C language was used in the development of the control software. Inter-process cooperation used typical client-server relation. The concurrent processes were created.

The main processes are: *leg* process, *driver* process and *sensor* process. The *leg* process is the client, *sensor* and *driver* processes are their servers. The *leg* process is responsible for generation of motion trajectories according to the rules given by the programmer and according to the data received from the *sensor* process which reads the data delivered by force sensor. The *driver* process is responsible for co-operation with hardware. It receives the data and command from the *leg*, transforms that data to the format acceptable by hardware (motion controllers) and communicates with hardware. By the return-paths (from servers to clients) are send only the *sensor* data (from *sensor* process), confirmation of the movement done (from *driver* process) or the information about the errors which can be hardware or software type – Fig. 12.

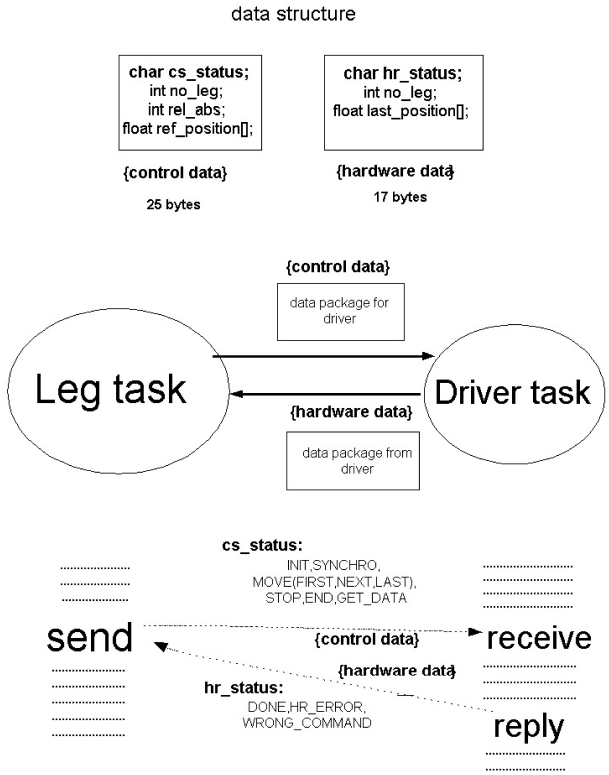

Fig. 12. Cooperation of control tasks

Control system was successfully implemented in the group of autonomous walking machines GROVEN [10] – Fig. 13. The details on control and self navigation method are given in [9, 10].

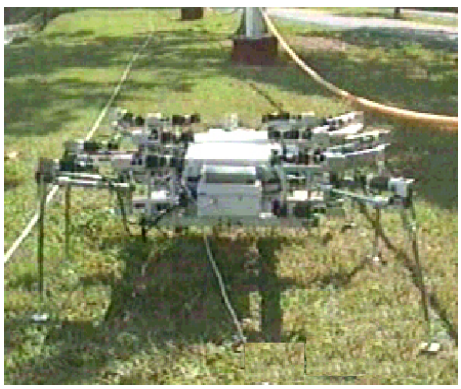

Fig. 13. The GROVEN hexapod

7. Role of the properly designed foot

Biologically inspired symmetric gaits produce the fastest displacements of walking machines. In hexapod robots those gaits are statically stable, but in quadrupeds and bipeds the dynamical effects decide about postural stability. The role of the foot during fast, efficient gaits can not be neglected but till our days it was not much discussed. The legs of multi-legged walking machines have usually 2 or 3 active degrees of freedom. The additional degrees of freedom (if introduced) are passive. The foot compliance is typically obtained using springs. Many multi-legged robots have feet shaped as balls or as a rotating plates [11].

The feet are attached to the shank by passive prismatic joints – Fig. 14. More complex designs consist of 3 passive DOF's [6]. The potentiometers are sometimes utilized as sensors for monitoring the joint positions – Fig. 15.

The biologically inspired foot with three fingers and 2 active DOF's (Fig. 16) is a unique [12] example of a more complex structure. In gait synthesis the attention is paid to the positioning of active joints.

The spring loaded foot was proposed and analyzed. The foot (or foot sole) and shank (or foot upper part) is connected by the spring. This endows the leg with compliance – the spring length changes proportionally to the vertical force. This change is small, but produces postural equilibrium. The theoretical analysis of contribution to postural stabilization is given in [13]. Recently the spring loaded foot with actuated spring loading was tested in the small biped [14] developed by our research group – Fig. 7.

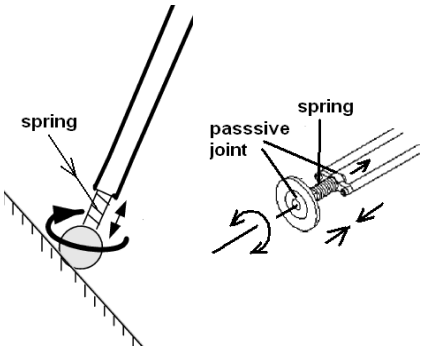

Fig. 14. Foot shaped as a ball or as a plate

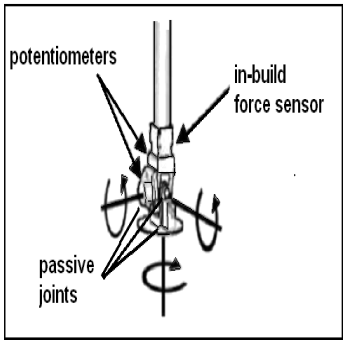

Fig. 15. Leg-end joint with 3 DOF's

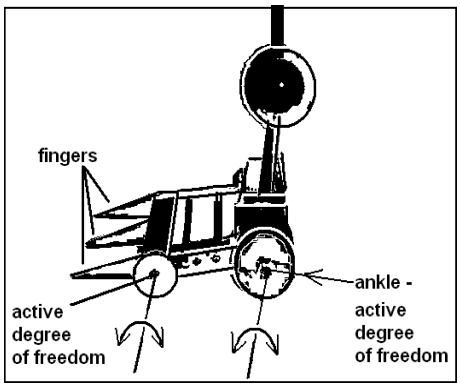

Fig. 16. Biologically inspired foot design

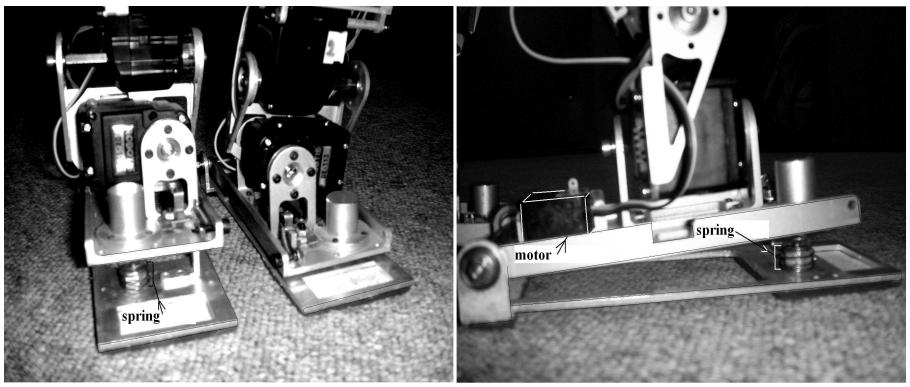

Fig. 17. Spring loaded foot

8. Conclusions

In this work are presented the key factors which must be considered during the walking robots prototyping. The proper choice of the motors is very crucial for walking robots – the devices with many active degrees of freedom (what required many motors) which are carrying its power supply. Moreover the motors not only contribute to the motion but in a big extend they must carry the body weight what is not the case of industrial manipulator. The mistake in motors evaluation can result in the prototype with limited mobility or without any ability to move in extreme case. Implementation of force control together with generation of leg-end reference forces is crucial for the synthesis of terrain adaptive motion. Due to large number of motors, sensors and many feedback loops the proper, systematic approach in control system development is needed. Last but not least the proper design solutions can improve the robot performances increasing the mobility and decreasing the energy spending. As it was signalled is can be obtained by introducing the foot or leg compliance what is the recent and very promising trend in robotics. The motors evaluation is addressed in details as the very important problem. This problem unfortunately is often neglected in publications. The other issues are shortly discussed with references to the publications describing them in the details. The aim of this work is to give the comprehensive overview of the topics useful in the walking machines prototyping. All presented results were confirmed by real tests in majority judged by the team of experts (the major part of presented work was performed within the frame of industrial project).

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