DYNAMICAL APPROACH TO THE DIAGONAL GAIT SYNTHESIS: THEORY AND EXPERIMENTS

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Abstract:

The method of two-legged diagonal gait synthesis for the quadruped robot is introduced. The problem of dynamic postural equilibration taking into account the role of compliant feet is solved. The equilibrium conditions are split to the feet attachments points and the points within the feet-end area. In simulation example the slip avoidance condition is tested. Presented method has the meaning for motion synthesis taking into account the robot parameters and - for the design of the feet considering the dynamically stable gaits. The method was proved by using simulations and experiments.

Keywords: *quadruped robot, diagonal gait, postural equilibrium, force distribution, computer simulation.*

1. Introduction

Many works concerning multi-legged walking machines are devoted to the design problems and to the motion generation principles of statically stable locomotion (i.e. [1, 3, 4, 5, 7, 10]). The control aspects are also discussed [14, 15, 16]. Our thorough search bringed brought no publications on the analysis of equilibrium conditions for the dynamical gaits considering stabilizing role of the foot.

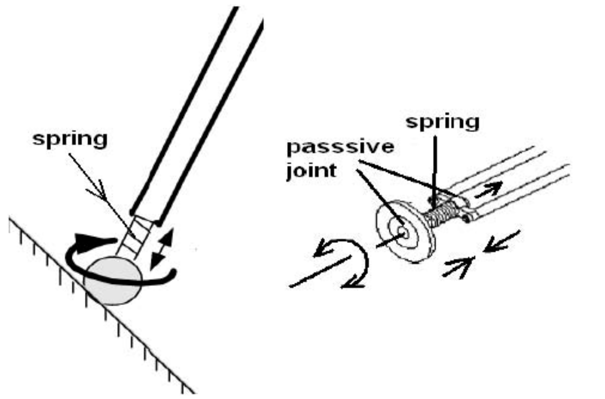

Fig. 1. Foot shaped as a ball or as a plate.

The legs of multi-legged walking machines have typically 2 or 3 active degrees of freedom. The additional degrees of freedom (if introduced) are passive. The foot compliance is typically obtained by using the springs. Many multi-legged robots have feet shaped as balls or as a rotating plates [13].They are attached to the shank by passive prismatic joints - Fig. 1. More complex designs consist of 3 passive DOFs [2]. The potentiometers are sometimes utilized as sensors for monitoring the joints position - Fig. 2. The biologically inspired foot with three fingers and two active DOFs - Fig. 3 is the unique [6] example of the more complex structure. In gait synthesis the attention is paid to the positioning of active joints. The role of foot and its passive DOFs during the walk of multi-legged machine is often neglected. On the other hand the usefulness of passive joints and springs in walking machines have been confirmed by practical experience. In this article we discuss the role of passive joints in maintaining the postural dynamical stability. Theoretical considerations are supported by simulation, and the results were validated by experiments.

2. Problem statement

The foot considered in our work is illustrated by the Fig. 4. In prismatic joint connecting the foot with the shank the spring is mounted. This brings the leg compliance, because the spring length changes proportionally to the vertical force. The length change is small but it supports the postural equilibrium, as it will be discussed further.

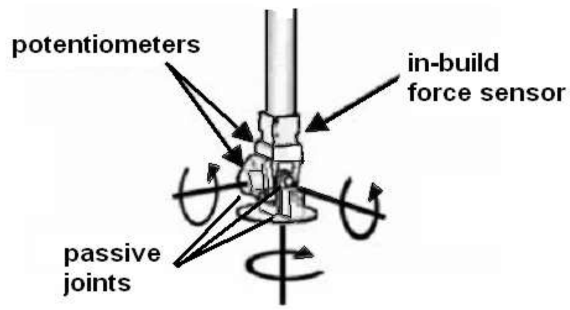

Fig. 2. Leg-end joint with 3 DOFs.

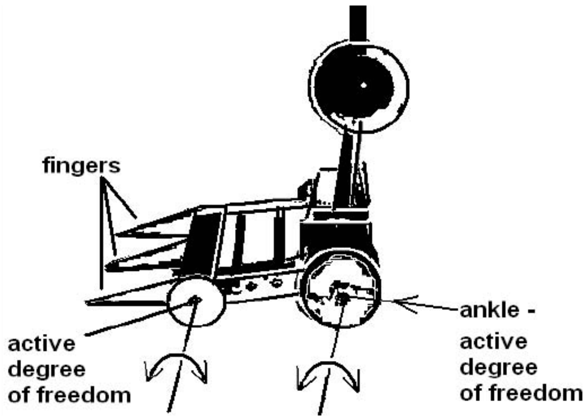

Fig. 3. Scheme of the foot inspired by the animals build.

Let's assume that $OXYZ$ is non-moving reference frame, $RXYZ$ is the frame attached to the robot trunk.

Coordinates of the robot mass centre ${}^{R}(xyz)_{CG}$ are equal to:

$$^{R}(xyz)_{CG} = \frac{m_o \ ^{R}(xyz)_o + \sum_i \sum_j m_{ij} \ ^{R}(xyz)_{ij}}{m} \quad (1)$$

where $^{R}(xyz) = \{^{R}x, ^{R}y, ^{R}z\}$, m_0 – mass of trunk, $m = m_0 + \sum_i \sum_j m_{ij}$ – total mass. To illustrate the method we will consider the prototype quadruped with dimensions and masses distribution illustrated in Fig. 4 (dimensions are expressed in mm). Lower script si denote the supporting leg. In considered diagonal gait the supporting legs are 1 and 4, or 2 and 3, where 1 denotes left front leg, 2 - is the right front leg, 3 - left hind leg, 4 - right hind leg. In further considerations $s1$ and $s2$ will mark the pair of supporting legs (for $s1=1$ is $s2=4$, and for $s1=2$ is $s2=3$).

Force equilibrium conditions are usually expressed in external reference frame $OXYZ$. They can be easily transformed to the local frame $RXYZ$ [12]. In frame $RXYZ$ the conditions are expressed as:

$$\sum_i {}^{\mathbf{R}}\mathbf{f_{si}} = \mathbf{F_e} + m({}^{\mathbf{R}}\ddot{\mathbf{r}}_{\mathbf{CG}} + {}^{\mathbf{R}}\mathbf{g}) =$$
$$= \mathbf{F_e} + m_0 {}^{\mathbf{R}}\mathbf{g} + \sum_i \sum_j + m_{ij}({}^{\mathbf{R}}\ddot{\mathbf{r}}_{\mathbf{ij}} + {}^{\mathbf{R}}\mathbf{g}) =$$
$$= \mathbf{F_e} + {}^{\mathbf{R}}\mathbf{f_{CG}} = [{}^{R}fx^{e}_{CG}, {}^{R}fy^{e}_{CG}, {}^{R}fz^{e}_{CG}]^T \quad (2)$$

where ${}^{\mathbf{R}}\mathbf{g} = {}^{R}T_O[0,0,-g]^T$, g is the gravity constant. ${}^{R}T_O$ is transformation matrix from $OXYZ$ to $RXYZ$. ${}^{\mathbf{R}}\mathbf{f_{CG}}$ is the resultant force vector acting to the robot mass centre. ${}^{\mathbf{R}}\mathbf{F_{si}} = [{}^{R}fx_{si}, {}^{R}fy_{si}, {}^{R}fz_{si}]^T$ is the force vector exerted by leg-end. The torques equilibrium conditions are expressed in frame $RXYZ$ by:

$$\sum_i ({}^{\mathbf{R}}\mathbf{r_{si}} - {}^{\mathbf{R}}\mathbf{r_{CG}}) \times {}^{\mathbf{R}}\mathbf{f_{si}} =$$
$$= \sum_i ({}^{\mathbf{R}}\mathbf{r_{si}} - {}^{\mathbf{R}}\mathbf{r_{CG}}) \times (\mathbf{F_e} + m({}^{\mathbf{R}}\ddot{\mathbf{r}}_{\mathbf{CG}} + {}^{\mathbf{R}}\mathbf{g})) =$$
$$= \sum_i ({}^{\mathbf{R}}\mathbf{r_{si}} - {}^{\mathbf{R}}\mathbf{r_{CG}}) \times (\mathbf{F_e} + {}^{\mathbf{R}}\mathbf{f_{CG}}) =$$
$$= [-{}^{R}M^e_x, \ -{}^{R}M^e_y, \ -{}^{R}M^e_z]^T \quad (3)$$

${}^{R}M^e_x$, ${}^{R}M^e_y$, ${}^{R}M^e_z$ are the external moments applied to the robot. In our considerations we assume only the rotation along vertical axis Z passing point R, I_{zz} is the main inertia moment around axis Z, and ϕ_Z is the rotation angle.

With the above assumption it is $-{}^{R}M^e_x = 0, {}^{R}M^e_y = 0$, ${}^{R}M^e_z = I_{zz}\ddot{\phi}_z$. Shortening, we denote $\mathbf{F_e} + {}^{\mathbf{R}}\mathbf{f_{CG}}$ by ${}^{\mathbf{R}}\mathbf{f^e_{CG}}$.

$$\mathbf{A} \ \mathbf{f} = \mathbf{F} \quad (4)$$

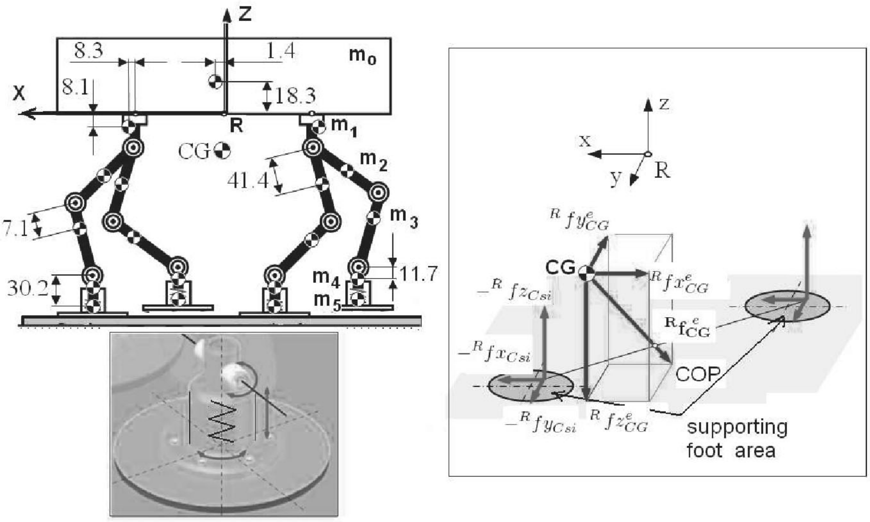

Fig. 4. View of the robot structure, its foot, and illustration of forces.

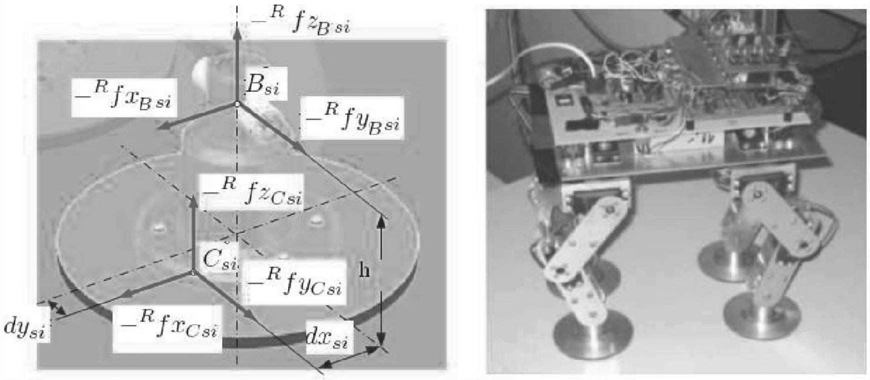

Fig. 5. Robot foot and applied notation, view of the prototype.

where

$$\mathbf{A}=\begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & -^{R}z_{s1} & ^{R}y_{s1} & 0 & -^{R}z_{s2} & -^{R}z_{s2} \\ ^{R}z_{s1} & 0 & -^{R}x_{s1} & ^{R}z_{s2} & 0 & -^{R}x_{s2} \\ -^{R}y_{s1} & ^{R}x_{s1} & 0 & -^{R}y_{s2} & ^{R}x_{s2} & 0 \end{bmatrix}$$

$$\mathbf{f}=[^{R}fx_{s1},^{R}fy_{s1},^{R}fz_{s1},^{R}fx_{s2},^{R}fy_{s2},^{R}fz_{s2}]^{T} \quad (5)$$

$$\mathbf{F}=[^{R}fx^{e}_{CG},^{R}fy^{e}_{CG},^{R}fz^{e}_{CG},^{R}M_{x},^{R}M_{y},^{R}M_{z}]^{T}$$
$$^{R}M_{x}=-^{R}fy^{e}_{CG}\,^{R}z_{CG}+^{R}fz^{e}_{CG}\,^{R}y_{CG}$$
$$^{R}M_{y}=^{R}fx^{e}_{CG}\,^{R}z_{CG}-^{R}fz^{e}_{CG}\,^{R}x_{CG}$$
$$^{R}M_{z}=-^{R}fx^{e}_{CG}\,^{R}y_{CG}+^{R}fy^{e}_{CG}\,^{R}x_{CG}-I_{zz}\ddot{\phi}_{z} \quad (6)$$

Matrix $\mathbf{A}$ is singular (rank($\mathbf{A}<6$), rank of extended matrix is 6 what means that equalities can not be fulfilled. The equilibrium conditions described by (2), (3) cannot be fulfilled considering only the legends. Taking into account the stabilizing role of the feet we split the conditions between points B_i and C_i of supporting legs. Passive joint in foot attachment allows the rotation along axis parallel to Y, but not rotation along axis parallel to X. Therefore, we can consider that to prevent the side trunk inclination the moment $^{R}M_x$ is compensated by forces exerted in points B_{si} of supporting legs. For evaluation of vertical leg-end forces we assume that the points B_i are located in constant distance $H-h$ from the plane RXY.

Taking into account ($^{R}z_{Bsi}=-H+h$), the forces equilibrium conditions, and condition for equilibrating the moment $^{R}M_x$ (2nd and 4th equality from rel. (4)) we obtain:

$$^{R}fz_{Bs1}=\frac{^{R}fy^{e}_{CG}(^{R}z_{CG}+h-H)}{^{R}y_{Bs2}-\,^{R}y_{Bs1}}+$$
$$+\frac{(^{R}fz^{e}_{CG}+2(m_4+m_5)g)(^{R}y_{CG}-\,^{R}y_{Bs2})}{^{R}y_{Bs2}-\,^{R}y_{Bs1}}$$
$$^{R}fz_{Bs2}=^{R}fz^{e}_{CG}+2(m_4+m_5)g\,-^{R}fz_{Bs1} \quad (7)$$

Now the forces $^{R}fz_{Bs1}$, $^{R}fz_{Bs2}$ are known. Using (3) the moments $^{R}M^{Bsi}_{x}$, $^{R}M^{Bsi}_{y}$ for both supporting feet can be easily obtained. Those moments must be compensated by feet compliance. We keep in mind that the rotations are only possible in passive joints located in points B_{si} (Fig. 5). The springs mounted in feet are bending under the exerted vertical leg-end forces. The active range of springs bend must be chosen to match the range of vertical forces. The springs bend introduces the stabilizing effect. Forces acting on mounting points B_{si} are accordingly transferred to the points C_{si} which are application points of reaction force vectors ($-^{R}fx_{Csi}$, $-^{R}fy_{Csi}$, $-^{R}fz_{Csi}$). Points C_{si} are translated in plane XY in relation to B_i (Fig. 5), that means $^{R}x_{Csi}=$ $=^{R}x_{Bsi}+dx_{si}$, $^{R}y_{C\,si}=^{R}y_{Bsi}+dy_{si}$ etc. The shifts dx_{si}, dy_{si} are such that the moments resulting from reaction forces towards B_{si} compensate the moments ($^{R}M^{Bsi}_{x}$, $^{R}M^{Bsi}_{y}$).

$$-\,^{R}M^{Bsi}_{x}=-^{R}fy_{Csi}\,h_i-^{R}fz_{Csi}dy_{si}$$
$$-\,^{R}M^{Bsi}_{y}=-^{R}fx_{Csi}\,h_i-^{R}fz_{Csi}dx_{si} \quad (8)$$

where h_i is the point B_{si} height over the ground considering spring shortening under the vertical force $^{R}fz_{Bsi}$. We keep in mind that $^{R}fz_{Csi}=^{R}fz_{Bsi}-(m_{i4}+m_{i5})g$, $^{R}fx_{Csi}=^{R}fx_{Bsi}$, $^{R}fy_{Csi}=^{R}fy_{Bsi}$. Now we define ^{R}COP- intersection point of $^{\mathbf{R}}\mathbf{f}_{\mathbf{CG}}$ with supporting plane (Fig. 4). This point is also the attachment point of resultant reaction force vector. During the real (physical) walk it is also the Centre Of Pressure (COP). In smooth walk (with smooth motion of the trunk) it is expected that $^{O}z_{COP}=^{R}z_{COP}=-H=\text{const}$. Point COP being the intersection of vector $^{\mathbf{R}}\mathbf{f}_{\mathbf{CG}}$ with plane $^{R}z_{COP}=-H$ has coordinates:

$$^{R}x_{COP}=^{R}x_{CG}-\frac{^{R}fx_{CG}}{^{R}fz_{CG}}(H+^{R}z_{CG}) \quad (9)$$

$$^{R}y_{COP}=^{R}y_{CG}-\frac{^{R}fy_{CG}}{^{R}fz_{CG}}(H+^{R}z_{CG}) \quad (10)$$

In stable posture the moments $^{R}M_x$, $^{R}M_y$ results from reaction forces, and evaluated in supporting plane towards the reference point COP shall be equal to zero:

$$^{R}Mx_{COP}=(^{R}y_{Cs1}-^{R}y_{COP})^{R}fz_{Cs1}+$$
$$+(^{R}y_{Cs2}-^{R}y_{COP})^{R}fz_{Cs2}=0 \quad (11)$$

$$^{R}My_{COP}=(^{R}x_{Cs1}-^{R}x_{COP})^{R}fz_{Cs1}+$$
$$+(^{R}x_{Cs2}-^{R}x_{COP})^{R}fz_{Cs2}=0 \quad (12)$$

Now, considering (11) and (12), and 3rd equality from (4) we obtain:

$$^{R}fz_{Cs1}=\frac{^{R}fz^{e}_{CG}\,(^{R}y_{COP}-\,^{R}y_{Cs2})}{^{R}y_{Cs1}-^{R}y_{Cs2}}=$$
$$=\frac{^{R}fz^{e}_{CG}\,(^{R}y_{COP}-\,^{R}y_{Bs2}-dy_{s2})}{^{R}\Delta y_{Bs1}+dy_{s1}-dy_{s2}}$$
$$^{R}fz_{Cs1}=\frac{^{R}fz^{e}_{CG}\,(^{R}x_{COP}-\,^{R}x_{Cs2})}{^{R}x_{Cs1}-^{R}x_{Cs2}}=$$
$$=\frac{^{R}fz^{e}_{CG}\,(^{R}x_{COP}-\,^{R}x_{Bs2}-dx_{s2})}{^{R}\Delta x_{Bs1}+dx_{s1}-dx_{s2}} \quad (13)$$

where $^{R}\Delta x_{Bs1}=^{R}x_{Bs1}-\,^{R}x_{Bs2}$, $^{R}\Delta y_{Bs1}=^{R}y_{Bs1}-$ $-\,^{R}y_{Bs2}$.

Remembering that using the expressions (7) the forces $^{R}fz_{Csi}$ ($^{R}fz_{Csi}=\,^{R}fz_{Bsi}-g(m_4+m_5)$) are also obtained, we rearrange each equation (13) separately, to obtain:

$$dy_{s1}=\frac{^{R}fz^{e}_{CG}\,(^{R}y_{COP}-\,^{R}y_{Bs2})}{^{R}fz_{Cs1}}-$$

$$-^{R}\Delta y_{Bs1}-dy_{s2}\frac{^{R}fz_{Cs2}}{fz_{Cs1}}=a_y-dy_{s2}\frac{^{R}fz_{Cs2}}{fz_{Cs1}}$$

$$dx_{s1} = \frac{{}^R fz^e_{CG}\left({}^R x_{COP} - {}^R x_{Bs2}\right)}{{}^R fz_{Cs1}} -$$

$$-{}^R \Delta x_{Bs1} - dx_{s2}\frac{{}^R fz_{Cs2}}{fz_{Cs1}} = a_x - dx_{s2}\frac{{}^R fz_{Cs2}}{fz_{Cs1}} \quad (14)$$

Substituting (14) to (8) and rearranging the terms we have:

$$dy_{s2} = = \frac{{}^R fy^e_{CG}h - {}^R M_x^{Bs1} - {}^R M_x^{Bs2}(h_1/h_2) - {}^R fz_{Cs1}a_y}{{}^R fz^e_{CG}(1-(h_1/h_2))}$$

$$dx_{s2} = = \frac{{}^R fx^e_{CG}h - {}^R M_y^{Bs1} - {}^R M_y^{Bs2}(h_1/h_2) - {}^R fz_{Cs1}a_x}{{}^R fz^e_{CG}(1-(h_1/h_2))} \quad (15)$$

The moments ${}^R M_x^{Bsi}$ equilibrated by feet can be obtained expressing (2), (3) for each foot separately, that means:

$${}^R M_x^{Bsi} = ({}^R y_{CG} - {}^R y_{Bsi}){}^R fz_{Bsi} + (H - h_i){}^R fy^e_{CG}$$

$${}^R M_y^{Bsi} = -({}^R x_{CG} - {}^R x_{Bsi}){}^R fz_{Bsi} - (H - h_i){}^R fx^e_{CG} \quad (16)$$

After calculation of those moments, the relations (15) will be applied to calculate dy_{s2}, dx_{s2} first and then, on a basis of (14), values of dy_{s1}, dx_{s1} will be obtained. Now the relations (8) can be used to bring the remaining force components (besides of already calculated vertical forces ${}^R fz_{Csi}$).

3. Simulation research

Robot structure and its mass distribution are given in Fig. 4. Leg has 3 active DOFs -2 in the hip and 1 in the knee. As it was mentioned shank and foot are connected by passive joint. The attachment uses in-build vertical spring (Fig. 5). Robot and its control system was described in [8, 9], in [11] the motion properties were discussed. The robot trunk length is $l_0 = 0.25$ [m], width $- w_0 = 0.18$ [m], thigh and shank lengths $- l_2 = l_3 = = 0.08$ [m]. Total mass $- m = 2.522$ kg, trunk mass $m_0 = 1.382$ kg, mass of hip segment $- m_{i1} = m_1 = = 0.094$ kg, mass of thigh $- m_{i2} = m_2 = 0.034$ kg, mass of shank $- m_{i3} = m_3 = 0.08$ kg, foot masses: the upper part $- m_{i4} = m_4 = 0.017$ kg, the lower part $- m_{i5} = m_5 = 0.06$ kg. Those parameters were used in simulations. The results obtained for robot turning motion with rotation by $7.5^o/s$ are presented. The robot height was $H = 0.22$ [m]. Results are given in Fig. 6. The minimal friction coefficient expressed as $\mu_i = sqrt(({}^R fx_{Bi})^2 + ({}^R fy^2_{Bi})^2)/|{}^R fz_{Bi}|$ was also evaluated. Feet will not slip when the real coefficient is not smaller than μ_i.

The experimental confirmation of the feet role in postural stabilization is given by observed stable displacement of the device by diagonal gait. Having the dismounted feet machine will overturn when trying to move by that gait. This proves that the stable posture is obtained due to the shift of leg-end force vector within the sole area, as has been discussed in our work.

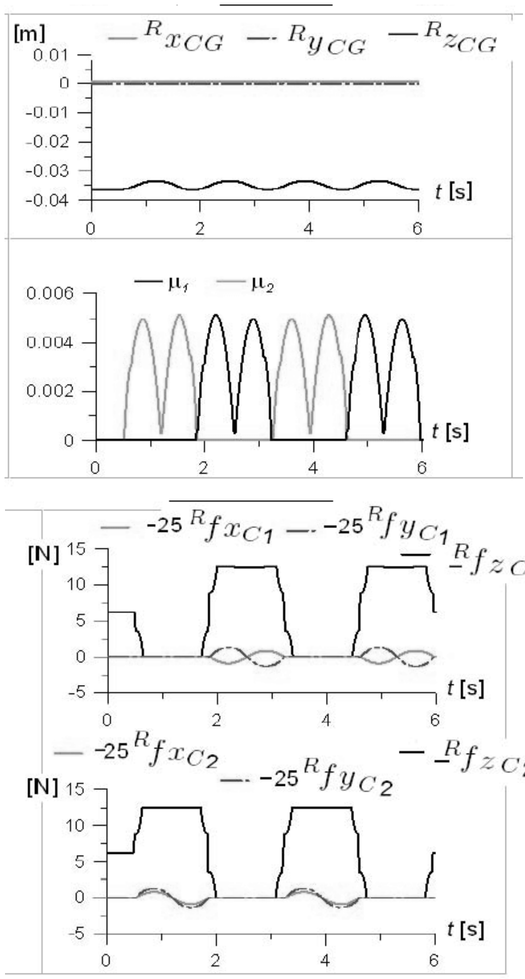

Fig. 6. Coordinates of COP, reaction forces and minimum friction coefficient.

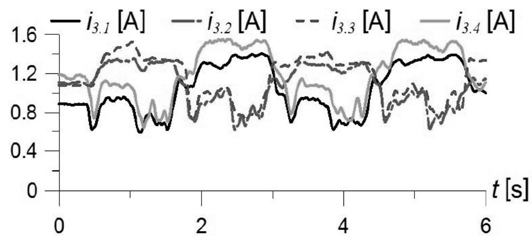

Fig. 7. Registered current in knee motor i_{3i} (motor no.3, i is the leg number).

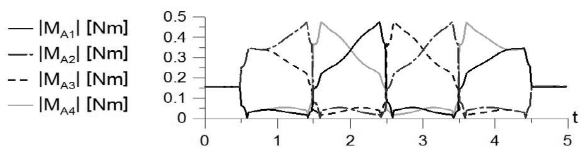

Fig. 8. Calculated torques for knee joint $- M_{Ai}$ (i is the leg number).

4. Conclusion

The motors current was monitored during the real gait. The current is proportional to the actuating torque. The torques was also evaluated using the inverse dynamics model and considering the forces obtained by the method discussed above. The measured current

(Fig. 7) and calculated torques (Fig. 8) exhibited similar regularities that prove the correctness of the presented method for leg-end forces evaluation.

The confirmation of the feet importance for postural stabilization was the stable walk observed for diagonal gait. The presented method of forces evaluation decomposes equilibrium conditions considering the feet attachments and feet-ends. Neglecting the condition for ${}^{R}M_z$ the rotation around daxis Z was allowed. In considered prototype (as in majority of quadrupeds) the feet are rotating freely, therefore the assumption has a logic confirmation. Postural stability observed during real machine motion by diagonal gait confirms the correctness of presented considerations. Obtained relations are useful for the walking machines design. The knowledge of leg-end forces translation dx_{si}, dy_{si} towards the feet mounting points has the importance for synthesis of dynamical stable gaits. The knowledge of those translations is necessary to evaluate if the foot supporting area will assure the postural stability. Relying on the given results the change the foot area or change of the leg configuration (changing the position of CG) can be adjusted for postural stabilization.

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References

[1] Gardner J.F., "Efficient Computation of Force Distribution for Walking Machines on Rough Terrain", *Robotica,* vol. 10, no. 5, 1992, pp. 427-433.

[2] Garcia E., Galvez J.A., Gonzalez de Santos P., "On Finding the Relevant Dynamics for Model-Based Controlling Walking Robots", *Journal of Intelligent and Robotic Systems*, vol.37, issue 4, 2003, pp. 375 -398.

[3] Klein C.A, Kittivatcharapong S., "Optimal Force Distribution for the Legs of a Walking machine with Friction Cone Constraints", *IEEE Trans. on Robotics and Automation*, vol. 6, no. 1, 1990, pp. 73-85.

[4] Martins-Filho L.S., Prajoux R., "Locomotion Control of a Four-legged Robot Embedding Real-time Reasoning in the Force Distribution", *Robotics and Autonomous Systems*, vol. 32, 2000, pp. 219-235.

[5] Pfeiffer F., Eltze J., Weidemann H.J., "Six-legged Walking Considering Biological Principles", *Robotics and Autonomous Systems*, vol. 14, 1995, pp. 223-232.

[6] Spenneberg D., Albrecht M., Backhaus T., Hilljegerdes J., Kirchner F., Strack A., and Schenker H., "Aramies: A four-legged Climbing and Walking Robot". In: *Proc. of 8th International Symposium iSAIRAS*, Munich, September 2005 (CD ROM).

[7] Takemura H., Deguchi M., Ueda J., Matsumoto Y., Ogasawara T., "Slip-adaptive Walk of Quadruped Robot", *Robotics and Autonomous Systems*, vol. 53, 2005, pp. 124-141.

[8] Trojnacki M., „Motion Description of Quadruped Robot", *Zeszyty Naukowe Politechniki Rzeszowskiej*, no. 222, Rzeszów 2005, pp. 357-364 (in Polish).

[9] Trojnacki M., "The Modeling, Programming and Computer Simulation of Motion for a Four-legged Robot". In: *Projektowanie Mechatroniczne*, Ed. T. Uhl, Wydawnictwo Instytutu Technologii Eksploatacji PIB: Kraków 2006, pp. 149-160.

[10] Zhou D., Low K.H., Zieliska T., "An Efficient Footforce Distribution Algorithm for Quadruped Walking Robots", *Robotica*, vol.18, 2000, pp. 403-413.

[11] Zielińska T., Trojnacki M., "Motion Synthesis of Dynamically Stable Two-legged Gait for a Quadruped Robot. Theoretical Considerations (1)", *PAR*, no. 11, 2007, pp. 5-11 (in Polish).

[12] Zielińska T., *Walking Machines: Fundamentals, Design, Control and Biological Patterns*, PWN: Warsaw, 2003, (in Polish).

[13] Zielińska T., Heng J., "Mechanical Design of Multifunctional Quadruped", *Mechanism and Machine Theory*, vol.38, 2003, pp. 463-478.

[14] Zielińska T., *Motion Synthesis. In Walking: Biological and Technological Aspects, CISM Courses and Lectures* no. 467. Ed. by Pfeiffer F., Zielinska T., Springer Verlag, 2004, pp. 151-187.

[15] Zielińska T., "Control and Navigation Aspects of a Group of Walking Robots", *Robotica*, Cambridge University Press, vol.24, 2006, pp. 23-29.

[16] Zielińska T., Heng J., "Real-time Control System for a Group of Autonomous Walking Robots", *Advanced Robotics*, vol.20, no.5, 2006, pp. 543-561.