11th International DAAAM Baltic Conference
"INDUSTRIAL ENGENEERING"
20-22nd April 2016, Tallinn, Estonia

MODELING HUMAN GAIT BASED ON MODEL PREDICTIVE CONTROL

Ovchinnikov I [1]; Minh VT [2] & Kovalenko P [1]

Abstract: *In this paper, models of 5-link and 7-link human gait have been used for studying the influence of feet on the general gait dynamics. Approximate trajectories of limbs have been calculated analytically with equation dynamics and their subsequent simplification for the human movements from their muscles and joints. The human activity is controlled by the central nervous system (CNS) and based on model predictive control (MPC). In our proposed models, MPC controller calculates the required moments at the joints, and these optimal moments are applied to the muscles. Here, MPC controller plays the role of the spinal cord in the human CNS. The results of simulation have been compared with several samples of real human gait obtained from motion captured systems. Based on this comparison, the possibility of further use of the model for personal identification and recognition of gait deviations are expected.*
Keywords: human gait modeling, gait recognition, MPC controller, 5-ling and 7-link mechanisms.

1. INTRODUCTION

Human walking is the most common and accessible kind of a daily load. Different people have different gait depending on the condition and physical characteristics of the person. Despite the fact that the dynamics of gait is common for all people, for every single person gait is unique, that makes it possible to use gait for personal identification. Recently, a great number of various models and artificial limbs have been developed. However, their design and development are based rather on intuition and further experimental validation than on fundamental theory. Such an approach is expensive, irrational, and ineffective.

Recently, particular attention has been paid to modeling of human and anthropomorphic robots gait, as well as to issues related to the development and production of orthoses and prostheses for human lower limbs [1-3]. The question of the application of lower limb movement simulation results for identification of people by their gait, as well as for recognition of various deviations and disorders in the musculoskeletal system, is of considerable interest [4-5].

In the majority of papers devoted to modeling of the gait, Lagrange's equations and some limitations are used for describing movements of the limbs, as the position of a 5-link or 7-link mechanism cannot be described only by dynamics equations. For example, in [6] movement of center of masses undertakes such limiting condition. In this paper the good results which are almost matching the experimental data were received, however paths of movement of some points are absolutely incorrect, and the computing circuit is very difficult because of what it is possible to use it only for human gait simulation without violations. In [7, 8] limiting condition is a condition of minimization of energy, in [9] are starting and finishing points and simplification of dynamic equations. In papers [9, 10] only the analytical method of calculation is used, and in [6–8] the MPC controller is used. Papers in which influence of the upper extremities on dynamics of gait is considered [11] are also known.

Within this paper it is offered to realize a combination of analytical computation of paths of movement of the lower extremities in a single-support phase with finding of the efforts and the moments required for such relocation by means of the MPC controller in case of simulation of gait of the person in the environment of Matlab/Simulink. The single-support phase is understood as a period when the person leans on one leg, and other leg is transferred. In case of movement of the person single-support and double-support phases sequentially alternate. In a double-support phase both legs lean on a surface on which movement is carried out [10, 12–13]. Modeling and calculation of applied MPCs are referred to in [14-15].

The structure of this paper is as follows: Section 2 briefs the mathematical modeling; Section 3 designs 5–link model; Section 4 designs 7–link model; in Section 5 results of simulation are provided; And finally conclusions are withdrawn in section 6.

2. MATHEMATIC MODEL

For simulation of movement of the lower extremities of the person it is necessary to know such characteristics of the researched object as weight, an inertia moment and length of extremities, and also initial and finite provisions of the person [4, 5].

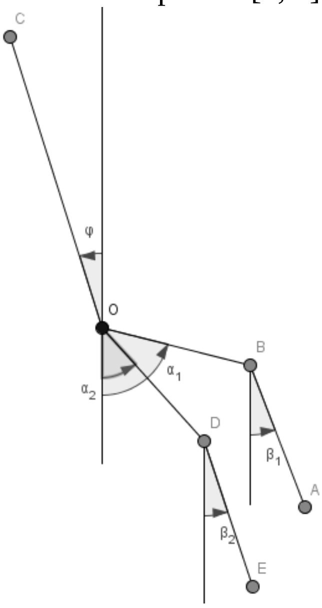

Fig.1 Angles of 5-link model

For the analytical description of movement of the person it is possible to use Lagrangian method of energy balance: Lagrangian (L) is the difference between the kinematic energy (T) and the potential energy (V):

$$L = T - V \qquad (1)$$

Kinematic energy of each link:

$$T = \frac{1}{2}(mv^2 + 2mp(\boldsymbol{v} \times \omega) + \Theta\omega^2) \qquad (2)$$

There m – mass of link, v – absolute velocity, ω – angular velocity, $\boldsymbol{v}$ – pole velocity, p – radius vector of the center of mass, Θ inertia moment relative to the pole. Total kinematic energy:

$$T = T_{OC} + T_{OB} + T_{BA} + T_{OD} + T_{DE} \qquad (3)$$

The potential energy:

$$V = g[My + K_r \cos(\psi) - \sum_{i=1}^{2}(K_a \cos(\alpha_i) + K_b \cos(\beta_i))] \qquad (4)$$

Fig. 1 shows the angles of rotation relative to the vertical links chosen for solutions following equations [9]. Lagrange's equations can be written in matrix form:

$$B(z)\ddot{z}_i + gAf_1(z) + D(z)f_2(\dot{z}) = C(z)\omega \qquad (5)$$

Here the matrix B(z) – the symmetric and positively certain matrix which it is possible to call a matrix of kinetic energy, A – a scalar matrix of potential energy, D(z) is a matrix of characters of Christoffel of the first kind for a matrix B(z), z=[φ α_1 α_2 β_1 β_2]^T – slope angles of parts of a body of rather vertical axis. φ – chest slope angle, – ,α_1, α_2 slope angles of the first and second hips, β_1, β_2 – the first and second shins, respectively. ω – the moments and responses in connections (joints) and support: u_1, u_2 – the moments in connection of shins and hips of the first and second leg, q_1, q_2 – the moments in connection of the casing with the first and second hip, P_1, P_2- the moments of forces applied to the first and second shins, respectively, R_{2x}, R_{2y}– horizontal and vertical component forces of response of the support operating on a supporting leg from a surface on which relocation is carried out [9, 10].

Movement z_i and $\dot{z}_i$ are small and system (5) can be linearized around points $z_i = 0$, $\dot{z}_i = 0$, $(i = 1, \ldots, 5)$, then:

$$\ddot{z}_i \cdot B_l + g \cdot A \cdot z_i = C_l \cdot \omega \qquad (6)$$

With $\omega(t) = 0$ ballistic motion equations can be received for 5-link model [9]:

$$B_l \cdot \ddot{z}_i + g \cdot A \cdot z_i = 0 \qquad (7)$$

For system (7) can be realized linear non-singular transformation with constant coefficients:

$$z = RX \qquad (8)$$

And system (7) with transformations will take a form:

$$\ddot{x} + \Omega \cdot x = 0 \qquad (9)$$

Where Ω is diagonal matrix $5x5$. And for system (9) the decision can be received:

$$x_i(t) = \frac{x_i(T)\, sin(\omega_i T) + x_i(0)\, sin(\omega_i(T-t))}{sin(\omega_i t)} \qquad (10)$$

$$x_i(t) = \frac{x_i(T)\, sh(\omega_i T) + x_i(0) \cdot sh(\omega_i(T-t))}{sh(\omega_i t)} \qquad (11)$$

Use of the equations 10 and 11 depends on values λ_i – roots of a characteristic equation for matrix Ω.

The detailed solution and sequential simplification of these equations is provided in papers [9, 10]. As a result of the decision values of the generalized coordinate are defined. The data obtained thus can be used in case of further simulation of gait of the person in the environment of Matlab/Simulink.

3. 5-LINK MODEL

For implementation by the person of relocation in space it is necessary to define the current location, to analyze a path of future relocation, to work out necessary signals for muscles to realize the abbreviations required them in case of relocation. At the same time three problems are solved: the sensor task, the analytical task of finding of a path, the computing task of finding of the necessary moments for transition from a current status to the required status. For simulation it is supposed that the sensor task is already solved [7–11]. For the description of paths (the analytical task) the ballistic description of movement of a body considered above by means of Lagrange's equations is used. In spite of the fact that these paths are very similar to gait of the person, they in case of any starting and finishing points will differ from real movements of extremities of the person. Matlab/Simulink calculating the moments on the connections of 5–link model imitating joints, and modeling movement of the lower extremities of the person (fig. 2) was developed for approximation of estimated paths to real during execution of this research.

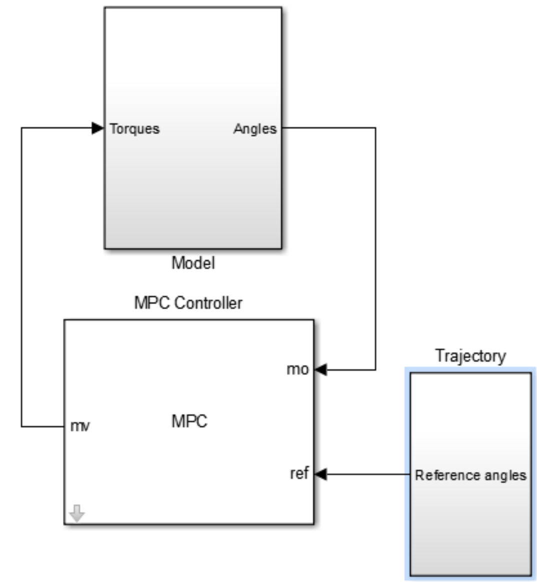

Fig.2 Matlab/Simulink scheme

Mathematical calculations of dynamics are automated and are executed in the Matlab program. In the diagram provided in fig. 1 in the block "Trajectory" (fig. 3) change of slope angles of a shin and hip in the course of movement is calculated.

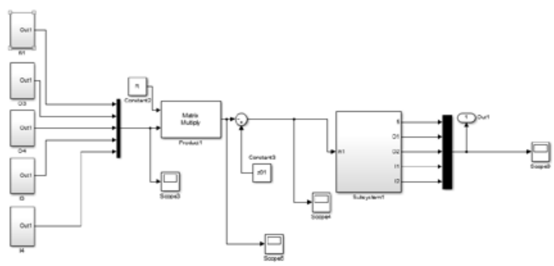

Fig.3 Trajectory block

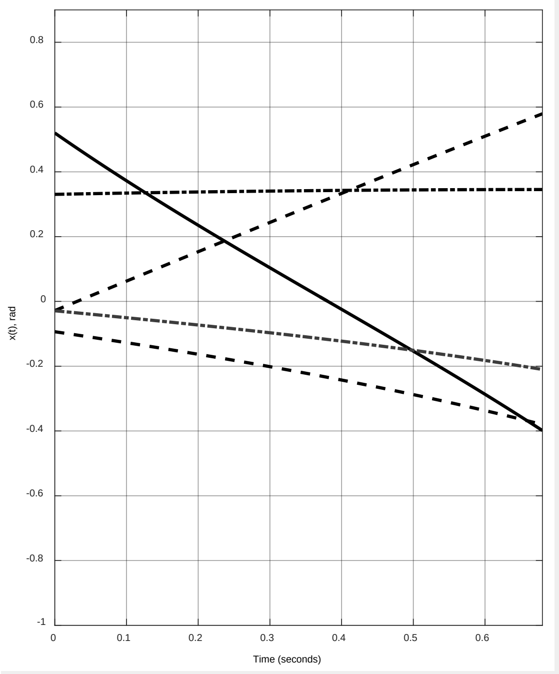

Fig.4 $x_i(t)$ computed in Simulink

In fig. 4 the calculated in "Trajectory" block values of the equations 9 and 10 depending on time are provided. The black straight line showed $x_1(t)$, grey dash line – $x_2(t)$, black dash line $x_3(t)$, grey chain line – $x_4(t)$, black chain line $x_5(t)$.

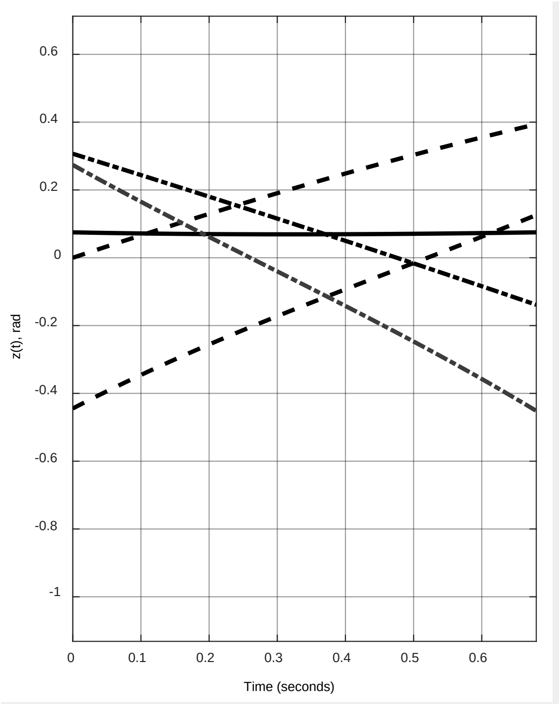

Fig.5 Mathematic trajectories

In a fig. 5 the calculated values in "Trajectory" block of the equation 8 depending on time are provided. The black straight line showed $\varphi(t)$, grey dash line – $\alpha_1(t)$, black dash line $\alpha_2(t)$, grey chain line – $\beta_1(t)$, black chain line $\beta_2(t)$.

These values are transmitted to the MPC controller (ref input). In the block "Model" there is a diagram of the 5–link mechanism in which the values of the required moments calculated by the MPC controller (mv) move. The model returns the current changes of angles of links (mo) to the controller.

4. 7-LINK MODEL

The 7–link model includes 5–link and feet on both legs if to neglect the mass of feet as their weight only several 100-th from all body weight and is commensurable with a measurement error of mass of remaining parts, then in Lagrange's equations influence of forces R_{2x}, R_{2y} will change, in particular they can be transferred to points of A and B, but will also create the additional moment:

$$P'_2 = -R_{2x} \cdot l_{2y} - R_{2y} \cdot l_{2x};$$

Where l_{2y}, l_{2x} – distances to a point of support S, as during movement S moves on foot under own law, it is problematic to count these parameters for the solution of the equations of Lagrange as a similar method, as for 5–link mechanisms, having created the equations from 7 variables. But as adding of feet influences generally the moments which are calculated the controller numerically, for 7–link model it is possible to set the same paths of movement for 5 links on condition that feet shall have small deviations from shins.

5. SIMULATION RESULTS

Thus, the model of the 7– link mechanism imitating gait of the person in a single-support phase on the basis of conditionally constant characteristics of the person and data on his initial and finite situation is received. Comparing of the experimental data and results of simulation (fig. 2) was made. As the experimental data the movement of the person written by means of the Vicon Blade program was used.

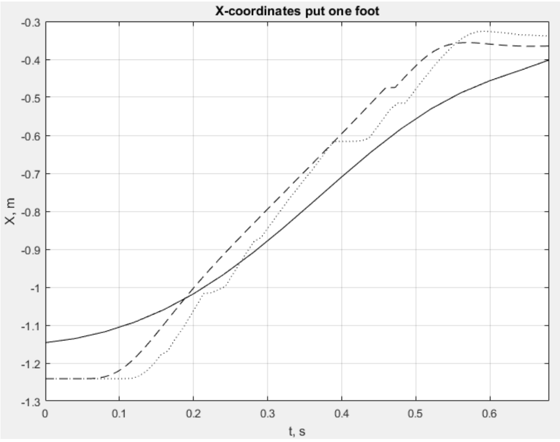

Fig. 4 X-coordinates of knee on swinging leg

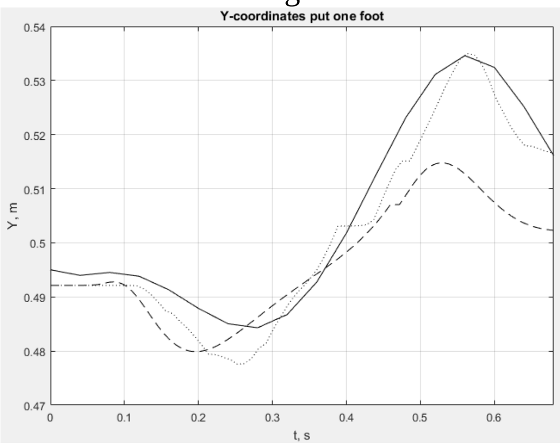

Fig. 5 Y-coordinates of knee on swinging leg

In fig. 4–7 diagrams of dependence of coordinates of reference and portable knees in a single-support phase on X axes from time are figured. The straight line showed results of experiment on capture of movement with use of Vicon Blade, dash line – results of 5–link simulation, dot line – results of 7–link simulation. Some initial errors in the provision of points are connected to complexity of simplification of the pilot model as links move in space, but not to the planes, and model only in the XY.

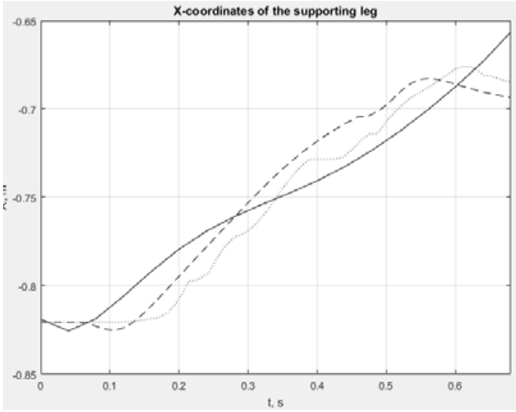

Fig. 6 X-coordinates of knee on supporting leg

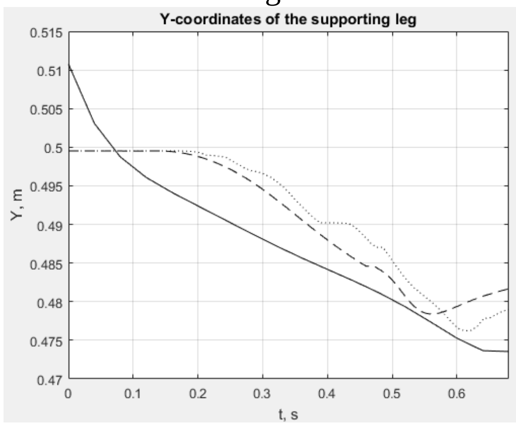

Fig. 7 Y-coordinates of knee on supporting leg

6. CONCLUSIONS

The analysis of results of simulation showed that the general dynamics of movement of the received model corresponds to movements of the real person, but there is an error which isn't exceeding 5 percent. This inaccuracy arises because of an error in case of determination of body weight and separate extremities, errors in finding of provision of the researched points as the person moves in three–dimensional space, and model in two–dimensional.

As further researches it is supposed to make similar model for a double–support phase and the whole step, to complicate model to 7– link by adding of feet, and also to study a possibility of application of results of simulation for the solution of the task of identification of the personality on gait and recognitions of deviations in operation of the musculoskeletal device.

REFERENCES

1. Gage J., Deluca P., Renshaw T. Gait analysis: Principles and applications. *Journal of Bone and Joint Surgery — American Volume* (1995), vol. 77. pp. 1607-1623.
2. McGeer T. Dynamics and control of bipedal locomotion. *Journal of Theoretical Biology* (1993), vol. 163, (3). pp. 277-314.
3. Vergallo P., Lay-Ekuakille A., Angelillo F., Gallo I., Trabacca A. Accuracy improvement in gait analysis measurements: Kinematic modeling. *in Proc.* IEEE Instrumentation and Measurement Technology Conference, Italy (2015). Art. no. 7151587. pp. 1987-1990.
4. Luengas L.A., Camargo E., Sanchez G. Modeling and simulation of normal and hemiparetic gait. *Frontiers of Mechanical Engineering* (2015) vol. 10 (3) pp. 233-241.
5. Gill T., Keller J.M., Anderson D.T., Luke R. A system for change detection and human recognition in voxel space using the microsoft kinect sensor. *Applied Imagery Pattern Recognition Workshop (AIPR*), (2011). pp. 1-8.
6. Sun J. Dynamic Modeling of Human Gait Using a Model Predictive Control Approach. *PhD Dissertation* Marquette University, (2015).
7. Ren L., Howard D., Kenney L. Computational models to synthesize human walking. *Journal of Bionic Engineering* (2006), vol. 3. pp. 127-138.
8. Ren L., Jones R., Howard D. Predictive Modelling of Human Walking over a Complete Gait Cycle. *Journal of Biomechanics* (2007), vol. 40 (7), pp. 1567–1574.
9. A. M. Formalsky, Relocation of anthropomorphous mechanisms, *Principal edition of physical and mathematical literature* (1982), (in Russian).
10. Tertychny-Dauri V. Y. Dynamics of robotic systems. Manual. *ITMO*, (2012), 128 pages, (in Russian).
11. Pontzer H., Holloway J.H., Raichlen D.A., Lieberman D.E. Control and function of arm swing in human walking and running. *Journal of Experimental Biology* (2009), vol. 212. pp. 523-534.
12. Mohammed S., Samé A., Oukhellou L., Kong K., Huo W., Amirat Y. Recognition of gait cycle phases using wearable sensors. *Robotics and Autonomous Systems* (2016). vol. 75. pp. 50-59.
13. Pappas I.P., Popovic M.R., Keller T., Dietz V., Morari M. A reliable gait phase detection system. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* (2001). vol. 9 (2), pp. 113-125.
14. Vu Trieu Minh, Afzulpurkar Nitin, & Muhamad, W. M. Wan, Fault Detection Model Based Controller For Process Systems, *Asian Journal of Control* (2011), 13(3), 382-397.
15. Minh, V. T. & Rashid, A. A., Modeling and Model Predictive Control for Hybrid Electric Vehicles, *International Journal of Automotive Technology* (2012), 13(3), 477-485.

ADDITIONAL DATA

Ivan Ovchinnikov[1] (author)
e-mail: ovi2745@mail.ru
Trieu Minh Vu[2] (co-author)
e-mail: trieu.vu@ttu.ee
Pavel Kovalenko[1] (co-author)
e-mail: kovalenko_p.p@mail.ru

[1]Department of Mechatronics, Saint Petersburg National Research University of Information Technologies, Mechanics and Optics, 49 Kronverksky Prospect, 197101, St-Petersburg, Russia.

[2]Department of Mechatronics,
Faculty of Mechanical Engineering,
Tallinn University of Technology,
Ehitajate tee 5, 19086, Tallinn, Estonia.