T H E A R C H I V E O F M E C H A N I C A L E N G I N E E R I N G

VOL. LVII 2010 Number 2

10.2478/v10180-010-0008-9

Key words: multibody simulation, bipedal robots, biomechanics, parameter identification

DANIELA FÖRG, HEINZ ULBRICH *

SIMULATION AND NUMERICAL PARAMETER IDENTIFICATION OF A BIOLOGICALLY INSPIRED BIPEDAL ROBOT WITH PASSIVE ELEMENTS

The goal of the project is to investigate the influence of elastic mechanisms on technical, bipedal locomotion. In particular, the paper presents the parameter identification for a biologically inspired two-legged robot model. The simulation model consists of a rigid body model equipped with rubber straps. The arrangement of the rubber straps is based on the arrangement of certain muscle groups in a human being. The parameters of the elastic elements are identified applying numerical optimisation. Thus two optimisation algorithms are investigated and compared with respect to robustness and computing time. Moreover, different objective functions are defined and discussed. The behaviour of the resulting configuration of the system is explored in terms of biomechanics.

1. Introduction

In the bipedal locomotion community, two different concepts are dominating. One concept is based on the idea of dynamic walking developed by McGeer [1]. These are minimally controlled robots containing passive elements. The second concept is the idea of fully actuated humanoid robots.

The first dynamic walking models consisted of an inner and an outer leg pair. Thus, the mechanism can fall fore- and backwards but not side wards. Nevertheless, the system is totally passive, and it is capable of walking down a slope without any external energy supply only driven by acceleration of gravity. Nowadays, the models comprise more joints, e.g. a knee or an ankle joint. Though the models are extended by actuated joints, most of the joints still remain non-actuated. The passive elements like springs for energy storage are preserved. Due to the energy supply, it is possible for these machines

* *Institute of Applied Mechanics Technische Universität München, Boltzmann Strasse 15, 85748 Garching, Germany. E-mail: foerg.d,ulbrich@amm.mw.tu-muenchen.de*

to walk on plane ground. Collins [2] developed an autonomous, very energy efficient, bipedal walking robot based on the passive dynamics walking concept. The hip and knee joints are non-actuated and can sweep through. The actuation is situated at the ankle joint. It consists of a DC motor and a spring which are connected through a lever mechanism. The control of the motor is realised as a state machine. So far, all passive robots are minimally controlled and can only move in one direction, without any correction of this direction. The robot Flame [3] from TU Delft, with his serial-elastic actuation, belongs to the new generation of the limit cycle walkers. Today, the idea of dynamic walking stands for building energy efficient machines which exhibit a natural gait.

Opposite to the idea of passive dynamic walking is the concept of fully actuated humanoid robots. This idea is originally based on classical industrial robots.

During the last years, impressive improvements in the field of actuators and computer technology enabled the development of high-performance humanoid robots. Well-known representatives of this concept are ASIMO [4] by Honda, HRP-2 [5] and HRP-3 [6] by Kawada Industries, Toyota's running robot [7] and Johnnie [8] and Lola [9] from TU München, Applied Mechanics. These robots are build of a rigid structure with revolute joints using electrical motors for actuation. For all robots, walking is a principal technology. One of the farthest developed humanoid robots is ASIMO (26 degrees of freedom, height 120 cm, weight 52 kg). At the end of 2005, it was reported that ASIMO could "run" with a speed of about 6 km/h, which shows that full actuated humanoid robots are capable of reaching high walking velocities. Though a dynamic walking motion can be achieved by these machines and small flight phases have already been demonstrated (ASIMO, HRP-2), some crucial points still remain open: natural fast walking or jogging, sudden change in direction, walking on rough terrain or jumping.

The goal of this study is to merge the concepts of the robots based on dynamic walking and classical humanoid robots. This is accomplished in this contribution by applying elasticities according to the JenaWalker concept [10] to a humanoid robots structure. In particular, the paper is structured as follows: first the multibody model and the arrangement of elasticities is presented. In the next chapter, the problem of unknown parameters is addressed, and the applied concept of numerical parameter identification is introduced. In chapter four, the results of a sensitivity analysis, as well as the investigated objective functions and optimisation algorithms are described. Finally, the conclusion summarises the paper.

2. Multibody simulation model

2.1. The basic model – a framework

The robot model is build with MBSim *, which is a multibody simulation platform developed at the Institute of Applied Mechanics. The simulation model consists of a sort of basic setup to which the actuation or passive elements can be applied in a modular way. The geometry and the number of degrees of freedom (dof) are inspired by the geometry of humanoid robots [9,11] developed at TU München. Thus, the system comprises 16 segments with 21 dof, where each leg has 6 dof, one at each shoulder, one at the pelvis and 6 dof for the upper body. The contact between the feet and the floor is represented by a point-to-plane contact, where each foot has four contact points, located at the corners of the foot. In the current simulation, an elastic contact model as well as a rigid contact model can be chosen. Spatial friction is considered by Coulombs law. Elastic elements are introduced into the basic model.

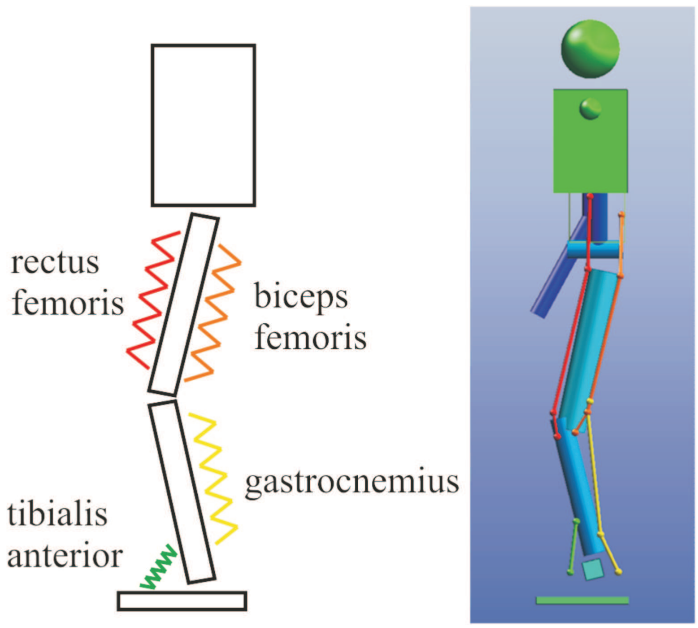


Fig. 1. Spring arrangement and simulation model

* MBSim is freely available under the GNU Lesser General Public License at http://mbsim.berlios.de

2.2. The elastic model

The arrangement of the elastic elements is biologically inspired. It is based on the concept of the JenaWalker II (JW) [10], where the bones of a human are represented by rigid elements, and the muscles are described by elements containing elastic and dissipative properties. The trunk of the JW is modelled as point mass. The elastic elements are realised as mono- and biarticular belts representing four major muscle groups: tibialis anterior (TA), gastrocnemius (GA), rectus femoris (RF) and biceps femoris (BF), see Fig. 1. These groups combine certain muscles: the RF represents the muscles m. recuts femoris, vasti (VS) and iliopsoas (IL) and the BF represents the group hamstrings (H) and gluteus (GL). At the hip joint, two DC motors are introduced to the system, thus the thighs can be kinematically actuated.

This idea is now applied to our basic model. As it can be seen in Fig. 1, the elastic elements are realised as mono- and biarticular rubber straps. Their arrangement is according to the one at JW. The rubber straps are modelled as unidirectional spring-damper elements with linear force law. Furthermore, the model for the biarticular element contains two mass-less, frictionless rolls for redirection of the force in the strap. Two DC motors with a state machine control are attached to the hip joints, as well. The actuators apply a torque with harmonic oscillation onto the thighs of the model. In addition, a motor is introduced at each shoulder in order to compensate the angular momentum around the vertical axis.

Although the arrangement of the straps is inspired by JW, there are some major differences, which bring along new aspects for the study. At first, the upper body of the JenaWalker model is restricted to move in the sagittal plane only, and trunk rotation is not allowed, whereas this simulation model is a three-dimensional model with the size and topology of a humanoid robot, and is not constrained at all. Moreover, the design of the spring arrangement can be adopted, but there is no rule where to apply the elements exactly, nor how to determine their characteristics. Therefore, after introducing the elements to the system, a set of parameters needs to be identified.

3. Parameter identification

3.1. The dimension of the problem

By applying four rubber straps to each leg of the model, two main problems are emerging: the first one comes with the dimension of the problem, namely four different stiffness, four damping factors, four unstretched spring length and 14 position vectors for the attachment of the belts leading to 36 parameters to be investigated. When examining the dynamic case (walking), this list of parameters has to be enlarged by the actuation characteristics: frequency, amplitude and initial angle.

To obtain a feeling for the model and the parameters, a first estimation is conducted by reducing the model to an inverted pendulum and investigating the static (standing) case. The pendulum (Fig. 2) is in equilibrium or in a stable position as long as the torque applied by the spring F_s is equal or greater then the torque applied by gravity F_g, see eq. 1.

$$mg\cos\alpha \leq 2ac\left(1 - \frac{l_0}{\sqrt{l^2 + a^2 + 2al\cos\alpha}}\right)\sin\alpha \tag{1}$$

The parameters are divided into spring characteristics represented by c or l_0 and geometrical parameters represented by a. When we choose a random parameter configuration, the stability region appears to be very small. When enlarging the distance a two times or raising the stiffness by ten, the stability region is enlarging rapidly. This leads to the assumption that at least some parameters are very sensitive for the system behaviour. This will be investigated in a sensitivity analysis. At a first attempt, a stable solution for the static as well as for the dynamic equilibrium is found by an extensive trail-and-error search. Since trail-and-error is not targeting for this problem, we are seeking for a systematic approach. The identification should be accomplished using optimisation algorithms in a loop with the multibody simulation.

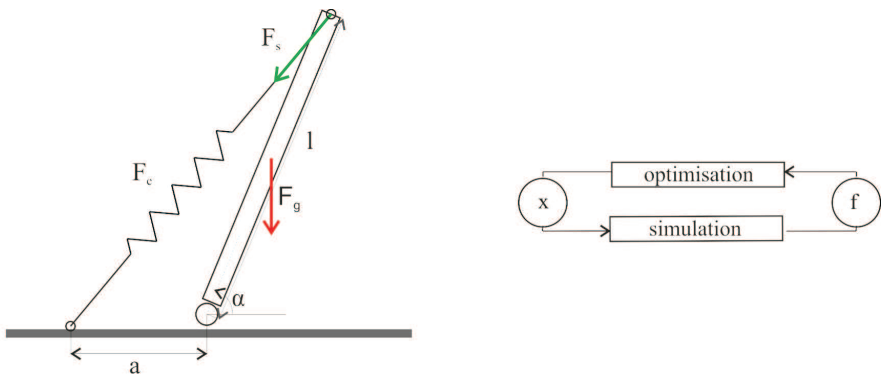


Fig. 2. Model inverted pendulum; optimisation – simulation – loop

3.2. The optimisation problem

Despite the fact that the objective function is the crucial point for every optimisation, there hardly exists a guideline which rules to obey when choosing the function. In the given case the function has the following characteristics: the function will only be numerically accessible, and it could also be non-smooth depending on the contact model. Since the robot model is a highly non-linear system, the function will have many local minima, and there will probably be more solutions to one problem. To gain some experience with the function, several objective functions are analysed, investigating single and multi criteria functions as well as different conjunctions. Besides, the time dependency of the problem is examined. To choose the right optimisation algorithms, the following points are considered. First,

$$\min_{x \in B} f(x)\; B := \{x \in R^n l_i \leq x_i \leq u_i \forall i = 1, \ldots, n\} \tag{2}$$

it should be possible to optimise more parameters at the same time. Furthermore, these parameters have to lie within reasonable boundaries, which leads to a constrained optimisation problem eq. 2, with x optimisation variable; the upper bound u and lower bound l, respectively. Two different optimisation algorithms are investigated for this identification. The implicit filtering algorithm from Kelly [12] and an evolutionary algorithm are applicable to this problem. Implicit filtering is a quasi-gradient based algorithm based on a projected quasi-Newton iteration, which uses difference gradients. The optimisation is carried out in Matlab (© 1994-2010 The MathWorks, Inc.) environment. The algorithms are linked with the MBSim model by starting a multibody simulation at each evaluation of the objective function, see Fig. 2. There, a varied parameter vector x, the parameters which should be determined, e.g. spring stiffness, are fed into the MBS model. After simulation, the value of the objective function f is determined, and transferred back to the optimisation algorithm.

4. Results

4.1. Proof of concept – Trail-and-Error

Taking into account the major differences from the JW model mentioned in Chapter 2, there exists no proof that the whole concept is working for a three dimensional, human-sized model with a trunk. Furthermore, there is no indication for a range of values for any of the parameters. Thus, at a first attempt, a set of parameters for the static and dynamic case is determined using trail-and-error. To decrease the number of unknown parameters, the position vectors as well as the actuation characteristics are taken for granted. Since we want to have a fast convergence, the damping value is set to a given magnitude. Thus, only spring stiffness and unstretched length remain to be determined. After an extensive trial-and-error search, a reasonable set of parameters is obtained. In Tab. 1 the resulting spring forces for the dynamic model are compared with the forces acting in a human muscle [13].

It is observed that the forces in the rubber straps match the forces acting in a human muscle quite well. The rubber strap stabilising the upper body, especially the RF, is higher then the corresponding biological element. This is motivated by different facts, e.g. in biology not only one muscle is responsible for stabilisation of the upper body. These results can be seen as a proof of the concept for this kind of arrangement, and give justification for further investigation of this model.

Table 1.

Muscle forces v.s. elastic elements

	human	robot
thigt(anterior)[kN] thigt(anterior)[kN]	RF 1.9 VS 6.9	RF 4.7
thigt(posterior)[kN] thigt(posterior)[kN]	BF 1.6 GL 3.6	BF 1.7
shank(posterior)[kN]	GA 1.4	GA 1.0
shank(anterior)[kN]	TA 1.3	TA 0.8

4.2. Sensitivity analysis

The unknown parameters can roughly be divided into two main groups: one containing the so-called "desired" parameters including the spring, geometrical and motor characteristics, and the second one of the "undesired" parameters, namely integration time and initial conditions. The "desired" parameters should be investigated in this chapter. To obtain a first meaningful range of parameters, a sensitivity analysis is performed. The static equilibrium is considered for this investigation. At the beginning of every analysis, the geometrical configuration of the joint angles and the fixed parameters is set to a start configuration. Furthermore, the objective function 5b from Tab. 2 is chosen with an integration time of 2s.

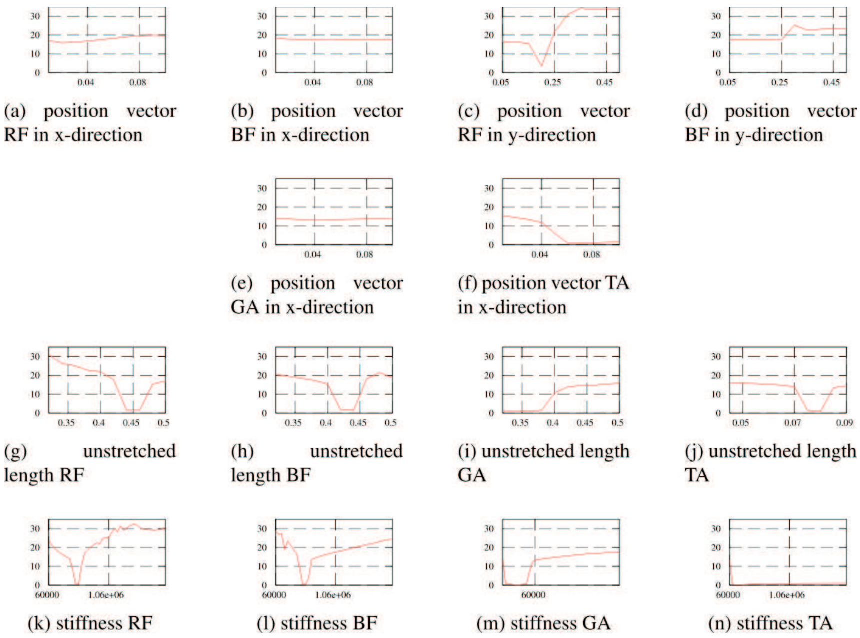
For the static equilibrium, three parameter characteristics are analysed: the position vectors where the springs are attached to the model, the spring stiffness and the corresponding unstretched length. In the first study, one parameter is varied, while in the second study the coupling of two parameters is investigated. Fig. 3a to 3f show the magnitude of the objective function over the variation of the x- and y- position of the position vector. It appears that the position of the spring in x-direction is neither sensitive for the RF (3a) nor for the BF (3b) or GA (3e). However, in the y-direction especially the RF exhibits sensitive behaviour. The unstretched length (3g to 3j) as well the stiffness (3k to 3n) are examined. Here different results are obtained. The

Table 2.

Summary objective functions

	$\mathbf{t}_{end}$ (a)	$\int \mathbf{dt}$(b)
single	keep center of upper body at constant height: y_0	
	$(y - y_0)^2$ (1a)	$\int (y - y_0)^2 \, dt$(1b)
	minimise velocity of upper body: u	
	u^2 (2a)	$\int u^2 \, dt$ (2b)
	minimise system kinetic energy: T	
	T (3a)	$\int T dt$ (3b)
	keep center of mass (COM) within contact area:	
	$0.5\ (x_1 - x_2) - x_{COM}$ (4a)	$\int 0.5\ (x_1 - x_2) - x_{COM} dt$ (4b)
multi	keep y_0 constant combined with minimise u	
	$2\|\|u\|\| + (y - y_0)^2$ (5a)	$\int (2\|\|u\|\| + (y - y_0)^2) \, dt$ (5b)
	$2\|\|u\|\| \cdot (y - y_0)^2$ (6a)	$\int (2\|\|u\|\| \cdot (y - y_0)^2) \, dt$ (6b)

values for the RF and BF (3g, 3h, 3k, 3l) are very sensitive. Besides, the stiffness of the TA (3n) is not sensitive at all.



(a) position vector RF in x-direction; (b) position vector BF in x-direction; (c) position vector RF in y-direction; (d) position vector BF in y-direction; (e) position vector GA in x-direction; (f) position vector TA in x-direction; (g) unstretched length RF; (h) unstretched length BF; (i) unstretched length GA; (j) unstretched length TA; (k) stiffness RF; (l) stiffness BF; (m) stiffness GA; (n) stiffness TA

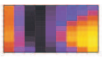
Fig. 3. One dimensional variation

In the next step, two parameters are varied at the same time. Since investigations of this kind are very time-consuming, and there would be over 90 different pairs possible, we constrain ourselves to special selected cases. We choose elements which are suspected to strongly influence each other like the counterparts RF and the BF as well as GA and TA elements. Here, we are specially interested in investigating very sensitive characteristics like the stiffness, but we also wanted to check if parameters which do not exhibit sensitive behaviour when analysed for itself suddenly change when studied in combination, like the positions vectors, RF in x-direction and BF in x-direction. Moreover, we are interested if there is a coupling of parameters within one element. Although the stiffness and the unstretched length of the RF appear to be very sensitive when studied for itself, it is not clear what happens when analysing a combination. Or on the other hand, what happens when we deal with the combination of the not very sensitive characteristics, stiffness and unstreched length, of the TA. The results for the two- dimensional variation are presented in Fig. 4. The dark colour indicates a low and the bright colour a high value of the objective function. All analysed pairs show a dependency between the parameters. A strong coupling was found for a combined variation of the points of attack of the springs in x-direction Fig. 4a, which was not expected, since for the one-dimensional search neither the RF nor the BF seemed to be sensitive. The strong dependency is also confirmed for the stiffness variation (4f, 4g). The minima in (4f) lie almost on the diagonal, which makes sense, since these two counterparts RF/BF have a nearly symmetric configuration. The last two plots show the results for the variation of different characteristics within one element. In the RF element, the coupling of c and l_0 has not as great influence on the result as in the TA element.

Summarising, this analysis has shown that there are certain parameters which are more sensitive then others. Moreover, these results imply that there is a strong influence of different parameters on each other. This has to be considered when choosing the parameters for the identification.

4.3. Objective functions

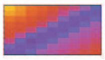
To gain further experience with the system behaviour, as well as to gain experience which objective function that is suitable for this problem statement, several objective function are investigated. For the investigation, the objective functions are divided into two main groups: “single” and “multi” criteria. The “single” one incorporates functions with one criterion to minimize, e.g. to minimize the kinetic energy of the system whereas the “multi” one combines two criteria. Furthermore, we distinguish the functions eval-



(a) position vector RF and BF in x-direction

(b) position vector RF and BF in y-direction

(c) position vector GA and TA in x-direction

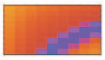


(d) unstretched length RF and BF

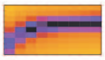
(e) unstretched length GA und TA

(f) stiffness RF and BF

(g) stiffness GA and TA



(h) combination stiffness and unstretched length RF



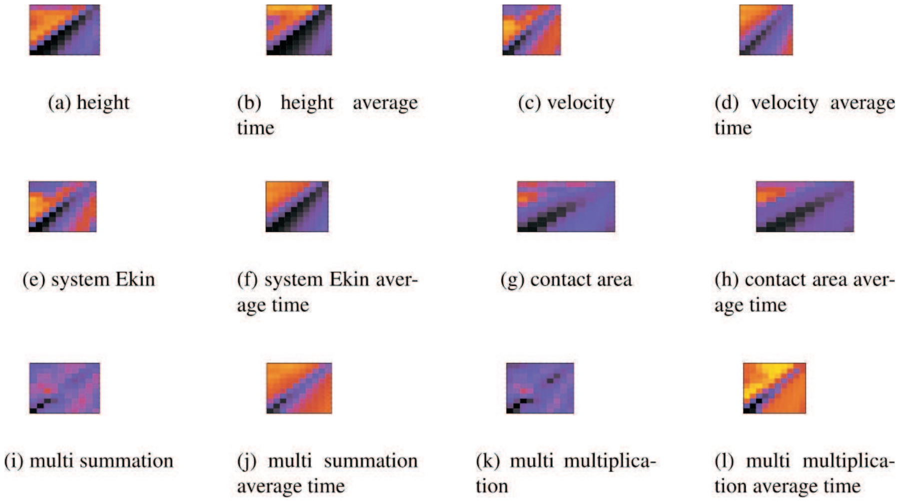
(i) combination stiffness and unstretched length TA

Fig. 4. Two dimensional sensitivity analysis

uated at the end of simulation time (a) and the summation over simulation time (b), in Tab. 2. The geometrical configuration of the static model was obtained by pre-integration, thus the initial configuration is the same during the whole investigation.

Since the results for the optimal values of the stiffness for the RF and BF are supposed to have nearly the same magnitude and to lie on the diagonal of the plots of the investigated objective functions, this value is chosen as a reference. For the investigation, the stiffness values of the RF and the BF are varied between 1e3 [N/m], lower bound and 1e6 [N/m], upper bound. The results are given in Fig. 5, where the stiffness of the RF and BF are depicted on the horizontal and vertical axis, respectively. The plots 5a to 5g show the objective functions for the single criteria. It can be observed that the quality of the solutions is varying from good to bad solutions.

The criteria (1) and (2) from Tab. 2 were applied to the multi-criteria study. The main focus of this investigation is on the way these two criteria are combined: using summation, see Fig. 5i and 5j or multiplication, see Fig. 5k and 5l, respectively. When using a combination of criteria, it seems to be important in what way the value for the objective function is obtained. For the (b) functions (average over time) in Tab. 2, the results lie clearly on the diagonal. However, at the (a) functions not all solutions are detected correctly. This becomes clear when thinking of summation in the terms of an "and" conjunction, meaning both criteria have to be fulfilled to give a good solution, and multiplication in terms of an "or" conjunctions meaning



(a) height

(b) height average time

(c) velocity

(d) velocity average time

(e) system Ekin

(f) system Ekin average time

(g) contact area

(h) contact area average time

(i) multi summation

(j) multi summation average time

(k) multi multiplication

(l) multi multiplication average time

Fig. 5. Objective functions

one criterion may not be fulfilled; the resulting value can still give a (false) minimum.

For the (a) version of the objective function, the result is strongly depending on integration time. In Fig. 6, the results for integration time of 1s and 2s are presented. For integration time 1s (left), not only can one observe the expected minima at the diagonal, but also encounter different, as the low values at the edges are projected to higher values.

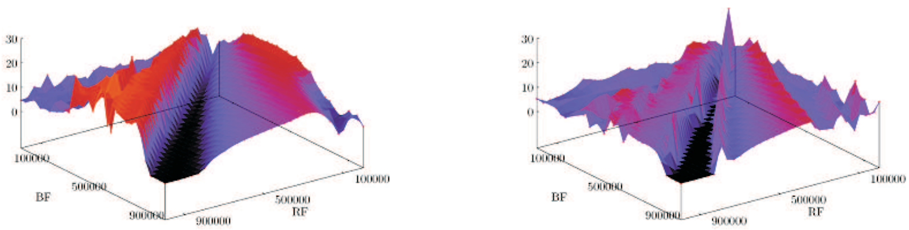


Fig. 6. Time dependency

Furthermore, the minima at the diagonal are “framed” by quite high values. These gradients come from the non-linearity of the system characteristics. For integration time 2s the model might have already reached an equilibrium position, but longer integration time means also longer computing time. Based on the presented results, the following optimisation algorithm investigation and parameter identification is conducted.

4.4. Optimisation algorithms

In this section, two different optimisation algorithms are analysed, with respect to optimisation time, number of function evaluations and quality of result. A good result is obtained as long as the objective function value is <0.5. At first, the static case is studied. For this study function 5b (Tab. 2) is chosen. At first, a two dimensional optimisation is performed. The stiffness of the RF and the BF should be identified using the implicit filtering algorithm (*imfil*). Different start values x_0 are investigated. The average results are contained in Tab. 3. It is observed that *imfil* most times finds an optimal value. For the four dimensional search, the stiffness of the RF, BF, GA and TA should be determined. Even though the parameters of the algorithm are varied and the search region is minimised, the values are much worse then the values for the two dimensional variation. This high mean value comes from a few very bad results.

Table 3.

Imfil

imfil	time	no. f	f value/quality
two dim.	1648s	121	0.32
four dim.	4070s	190	5.5

Table 4.

Evolution

case (pop/child/gen)	time	f value
A1. (10/10/10)	1107s	2.14
A2. (50/50/50)	25585s	0.044
A3. (100/100/50)	48009s	0.014
B (50/50/50)	18512s	0.38

The same investigations are accomplished using the evolutionary algorithm (*evolution*). Here, the number of population (pop), the number of children (child) and the maximum of generations (gen) is varied. Tab. 4 presents the results for the two and four dimensional identification. Case A 2 proved best in the relation computing time to quality. Population and children greater then 50 are too numerous for calculation (case A 3 and A 4) and a number lower then 50 does not give reliable results. Using the initial values of case A 2, the four dimensional problem was investigated; see "B" in Tab. 4. Though the f value is not as low as for the two dimensional analysis, the obtained solution is still a good one.

In the next step, the dynamic system should be investigated. Therefore, the objective function has to be adapted. The new objective function is a combination of "keeping upper body within a certain region" and a stop criterion. The stop criterion terminates if the height of the upper body becomes lower than a certain value. This is necessary to keep the optimisation time at a reasonable value, since the integration time is set to 5s for each optimisation step. If the integration is terminated by the stop function, the function value is set to the kinetic energy of the system. *Imfil* again gives good results for the two dimensional search, independent from the initial value. In fig. 7, the height of the upper body is plotted versus the integration time. The short lines at the right side of the plot indicate a termination by the stop criterion. The lines up to 5s indicate that the corresponding initial value gives a solution. This is an interesting result when looking at the four dimensional search. Here, no solution is identified. *Evolution* is investigated for the two and four dimensional dynamic case, as well. Taking a population of 50 and children of 50 gives good results again. The disadvantage of this algorithm is the long identification time.

When performing an identification, the choice of the correct algorithm depends on the problem formulation, the dimensions of the problem and the time to be available for the identification.

Imfil is much faster then *evolution*, but does not always identify proper sets of parameters, whereas *evolution* proved to be very reliable. The purpose of the optimisation algorithm investigation is mainly to show that it is possible to solve such a kind of problem with a gradient-based and an evolutionary algorithm. Depending on the problem, a combination of both algorithms should be considered and investigated.

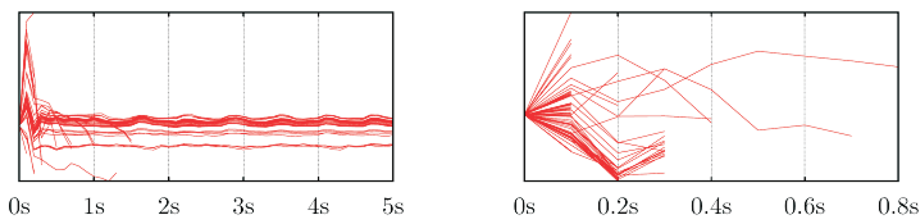


Fig. 7. Imfil dynamic

Finally, for an example set of identified parameters, the resulting robots motion is depicted in Fig. 8. Here, the parameters have been identified for the two-dimensional model.

5. Conclusion

In this paper, a biologically-inspired robot is investigated. The multi body model has the geometry of a humanoid robot, and is equipped with mono- and biarticular straps representing certain muscle groups. The system is actuated solely with two motors situated at the hip. By introducing passive elements into the model, one also introduces a lot new and unknown parameters, e.g. spring characteristics like stiffness. Since there is no rule how to determine these parameters, an identification applying numerical optimisation is performed. By trail-and error approach, a set of parameters is found for a static (standing) and dynamic (walking) equilibrium.

This is an evidence for the concept for the model, and it justifies further investigation. To obtain some experiences with the system and the unknown parameters a sensitivity analysis is conducted. It is shown that nearly all, but especially the elastic element parameters, are highly sensitive. Next, several objective functions are investigated. The functions according to (5b) and (6b) in tab. 2 give good solutions. However, studying the result according to (a) one must take into account the influence of the integration time. Finally, two different optimisation algorithms are analysed with respect to function evaluations, computing time and quality of result. The right choice of the algorithm depends on the dimension of the problem and time available for identification. In further investigations, the model of the rubber straps will be changed from a linear to nonlinear one. The actuation of the hip will be reduced to come closer to the concept of minimal control of passive dynamic walkers.

Acknowledgements

This project is supported by the German research foundation (UL 105/32-1). Furthermore, the author wants to thank Andre Seyfarth and his team from the Lauflabor in Jena for his inspiration and his help from a biomechanical point of view.

Manuscript received by Editorial Board, December 10, 2009;
final version, March 17, 2010.

REFERENCES

[1] McGeer T.: Passive Dynamic Walking. Int. J. Rob. Res. 9, 1990, p. 62.82.
[2] Collins S., Ruina A.: A bipedal walking robot with efficient an human-like gait. Proc. IEEE Int. Conf. Rob. Aut. (ICRA), 2005, p. 1983-1988.

[3] Hobbelen D., de Boer T., Wisse M.: System overview of bipedal robots Flame and TUlip: tailor-made for Limit Cycle Walking, Proc. Int. Conf. on Intelligent Robots and Systems Acropolis Convention Center, Nice, France, Sept, 22-26, 2008.
[4] Hirai K. et al.: The development of honda humanoid robot. Proc. IEEE Int. Conf. Rob. Aut. (ICRA), 1998.
[5] Kajita S. et al.: A hop towards running humanoid biped. Proc. IEEE Int. Conf. Rob. Aut. (ICRA), 2004.
[6] K. Kaneko et al.: Humanoid robot HRP-3, Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS), 2008, pp. 2471-2478.
[7] Tajima D., Honda R. and Suga K.: Fast running experiments involving a humanoid robot, Proc. IEEE Int. Conf. Robot. Autom. (ICRA), 2009, pp. 1571-1576.
[8] Löffler K. et al.: Sensors and control concept of walking Johnnie. Int. J. Rob. Res. 22, 2003.
[9] Lohmeier S., Buschmann T., Ulbrich H.: System design and control of anthropomorphic walking robot lola. IEEE/ASME Transaction on Mechatronics 14, 6 (2009), 658-666.
[10] Seyfarth A. et al.: Towards bipedal running as a natural result of optimizing walking speed for passively compliant three-segmented legs. in Proc CLAWAR Brussels, 2006.
[11] Lohmeier S. et al.: Modular joint design for a performance enhanced humanoid robot. Proc. IEEE Int. Conf. Intelligent Robots and Systems (IROS), 2006.
[12] Gilmore P., Kelley C.T.: An implicit filtering algorithm for optimisation of functions with many local minima J. Optimisation 5 (SIAM), 1995, p. 269-285.
[13] Winters J. M., Savio L-Y: Woo Multiple Muscle Systems – Biomechanics and Movement Organisation; Springer Verlag, New York, 1990, p.726-773

Symulacja i numeryczna identyfikacja parametrów inspirowanego biologicznie dwunożnego robota z elementami biernymi

S t r e s z c z e n i e

Celem projektu jest badanie wpływu elementów sprężystych na realizację techniczną dwunożnej lokomocji robota. W szczególności, w artykule przedstawiono identyfikację parametrów inspirowanego biologicznie modelu robota dwunożnego. W modelu uwzgldniono człony sztywne oraz gumowe taśmy. Rozmieszczenie taśm jest wzorowane na rozmieszczeniu odpowiednich grup mięśniowych u człowieka. Parametry elementów sprężystych są identyfikowane na drodze optymalizacji numerycznej. Zbadano dwa algorytmy optymalizacyjne, porównując je pod kątem uzyskiwanych wyników i czasu obliczeń. Ponadto, zdefiniowano iprzdyskutowano różne funkcje celu. Zachowanie się zoptymalizowanego układu zbadano w kategoriach biomechaniki.