BIO-INSPIRED LOW-COST ROBOTIC JOINT WITH REDUCED LEVEL OF BACKLASH AND A NOVEL APPROACH: THE EMULATED ELASTIC ACTUATOR

Theses of the *Ph.D.* Dissertation

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Budapest, 2013

1 Introduction And Aims

Research on biped robots is important for two reasons. On one hand to create walking robots that are able to assist the humanity. For example, in case of a catastrophe of a nuclear plant, that unfortunately lately happened at Japan's Fukushima Daiich, biped robot could be deployed to save human lives. On the other hand, research on biped robots could help us to better understand human locomotion disorders, for example locomotor rehabilitation for individuals with stroke, or how to improve lower-limb prostheses.

High-end humanoid biped platforms are extremely expensive. There are a few low-end commercially available two-legged robots, like the NAO from the Aldebaran Robotics, that are used in academic research. These robots are usually incorporating robotic joints made of standard parts. In terms of actuators, fabrication inaccuracy introduces significant mechanical backlash which is a hard-nonliearity from the control point of view.

Therefore, during my early research I tried to address the issue of non-linearities in the actuators of biped robots by attempting to create a bio-inspired low-cost robotic joint using PMSMs and low-level active control.

In addition to nonlinear phenomena, walking inherently implies dynamics that are not necessarily been addressed by the theory of classical robotics. In contrast to the industrial robots, walking, running or climbing stairs with a two-legged robot requires substantially different approaches.

A new field of robotics is emerging namely the *dynamic walking*. In 2006, a new international conference has established to allow researchers all over the world to share their findings. The central issues are the energy efficiency, dynamic stability and compliant actuation. Compliance is turned to be essential for the fundamental interaction with the environment. During the half-year, while I had the privilege to get involved in the research of James Schmiedeler's group at the Locomotion And Biomechanics Laboratory (Notre Dame), I understood the limits of the principles of classical robotics. After my returning to Hungary, I started to work on a novel concept that could improve the dynamics of biped robots.

Thus, during my late research I tried to investigate a new type of robotic actuator that can emulate the different kind of elasticities under software control or in other words, to be able to implement intrinsic compliance that is found to be crucial for dynamic movements.

With this new concept, unlike existing mechanical solutions, like SEA [8] that are limited to fixed elastic behaviour, change in the parameters of the elasticity could become available on the fly. Considering the fact that the springiness would being emulated in software, exotic non-linear functions would become realizable.

2 Methods Used in the Experiments

My research was motivated by the most recent results in the field of legged robotics. During the course of the work, I was dependent on knowledge gained from several interdisciplinary topics. In my work, it was very important to me that in addition to the theoretical description, I would also create working hardware implementations.

I made the symbolic description of the proposed systems with the help of Mathematica 8 from Wolfram Research Inc. The numerical analysis of the models was performed in Matlab 2010 from MathWorks Inc, where a number of toolboxes were a great help in the simulations. The operation of the electronic devices first was tested in National Instruments Electronics Workbench. To create the appropriate printed circuit boards Altium Designer 10 was used. On these boards, many various types of components, IC-s were used, which were controlled by PIC (16 and 32-bit) type microcontrollers from Microchip Inc.

Both the Permanent Magnet Stepper Motor (PMSM) and the Hybrid Stepper Motor (HSM) model was used to simulate the accurate behavior of the actuators. In the case of the Emaulated Elastic Actuator the model of the Hookean and the Kelvin-Vought type elasticities were used. During the investigation of the non-linear type elastic behaviour, the model of the proposed underactuated one-legged robot was formulated using the energy based Lagrange-Euler method. Solidworks 2010 was used as a CAD software and was in a great help to create working hardware implementations to support the simulation results.

3 New Scientific Results

1. Thesis: *Bio-inspired solution for a non-linear phenomenon of low-cost robotic actuators.*

Most robotic joints are actuated by rotational mechanisms. Typically, these mechanisms are driven by electric motors whose operating speed is higher than what the joints actually require. Therefore gearboxes are used to reduce the speed of the joints and also to increase their torque capability. The incorporation of a gearbox corrupts the continuity of the torque transmission because of the backlash phenomenon. Backlash originates from the gear play that results from the imperfectness of the fabrication or the increased wear level of the mating gears. In static cases the non-linear characteristic introduces only positioning inaccuracy but in dynamic cases even limit-cycles may occur, significantly degrading the performance of the feedback systems.

Compensation for the effect of the backlash using Stribeck friction was reported in [9] and [10]. Controllers and adaptive controllers for mechanical systems with backlash can be found in [11–13]. Backlash compensation for a humanoid robot with a disturbance observer [14], as well as with a genetic algorithm [15], were reported. Generally speaking, the most current solutions require an accurate time-varying model of the drives that is not available in the majority of practical cases. Therefore, in the high-end robotic actuators an expensive mechanical solution is used, the harmonic drive, to feature a near zero backlash.

The disadvantages of using this type of mechanical solution are its increased level of elasticity and its significantly higher cost. A typical humanoid robot requires tens of joints to be actuated therefore a cost-effective robotic actuator with reduced level of backlash is needed.

My approach is to use a pair of low-cost actuators instead of a harmonic drive. Then one actuator is dedicated for the right turn and the other for the left turn like the flexing and extending in the human limbs. A smooth motion could be realized with a proper control by mimicking a simple reciprocal innervation of the two muscle groups.

Related publication: [2].

1.1. I designed and implemented a PMSM based low-cost robotic joint that was inspired by the human flexor-extensor mechanism. I proposed a low-level algorithm that was proved to reduce the level of backlash by 90%.

In order to obtain good control performance even in the low-speed range, I have chosen Permanent Magnet Stepper Motors (PMSM) for the actuator that are commutated in a digital closed-loop fashion. Based on the defined backlash level of the drives a low-level algorithm is given to reduce the effective joint backlash, by utilizing the same controller that responsible for the closed-loop commutation. A five mass model of the joint, including the piecewise linear backlash model, and an accurate motor model is given to be able to investigate the algorithm. Numerical simulation of a continous back and forth motion was carried out, since the change in direction of the motion is very important. The reason for that is during the traverse of the backlash no torque is transmitted, but when the contact is reestablished the resulting impact on the mating gears may even damage the drive.

Fig. 1.(a) shows the noticible traverse of the backlash during a direction change and Fig. 1.(c) illustrates the simulation result after using the proposed backlash reduction algorithm. In order to support the theoretical results, I designed and implemented the proposed backlash reduction in real hardware. In Fig. 1.(b), one can see the experimental measurement of the very same motion, without reduction. And Fig. 1.(d) shows the measurement with reduction on. The results showed that the mean reduction

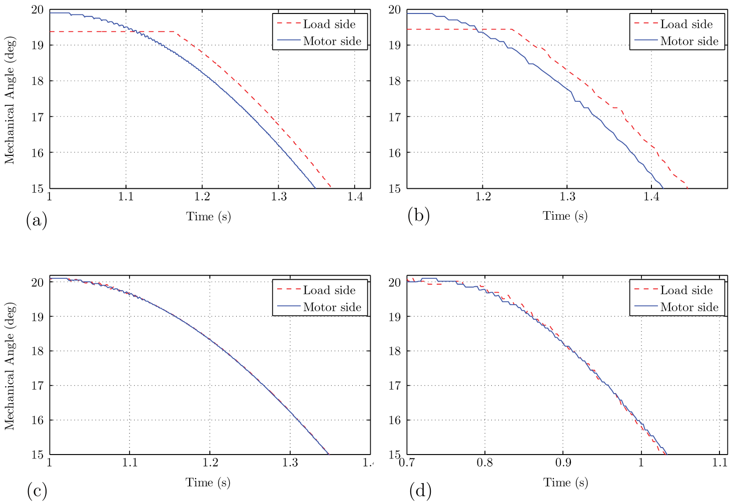

Figure 1: Side-by-side comparison of simulation (a,c) and experimental (b,d) results achieved with (c,d) and without (a,b) backlash reduction, during the direction change of the proposed robotic joint.

in the effective level of joint backlash was reduced by an order of magnitude.

Related chapter of the dissertation: II.

2. Thesis: *The novel concept of the Emulated Elastic Actuator.*

The classical robotics requires the transmission between the actuator and the load to be very stiff. But in the last decade the tradition of "the stiffer the better" seems to be changed. Nowadays compliant actuator designs are gaining increasing popularity. One of the reason for that is to overcome the limitations of a rigid transmission in terms of shock survivability, force control stability and human-safe operation. Maybe the most interesting and the one that had the greatest impact among these is the Series Elastic Actuator (SEA) [8]. It incorporates a physical spring at the output in series with a traditional actuator. Nevertheless, there is a significant limitation of the SEA concept, in order to change the intrinsic elasticity of the joint, the included physical spring must be disassembled and replaced with an appropriate.

In the light of the foregoing, I investigated the possibility of shaping the natural dynamics of the actuation system by high-speed local control. More precisely, to design and implement an actuator that is capable of emulating different types of elastic behavior, or in other words, to come up with a new concept of a universal actuator that can be used to change the way how it interacts with its environment.

Related publication: [7].

2.1. I proposed the concept of a novel fully electronic actuator that, in contrast to the Series Elastic Actuator used in the state-of-the-art dynamic walking robots, creates physical elasticity under local high-speed software control without the need of springs.

I proposed a new concept of fully electric emulation of joint elasticity for biped robots and for other applications (patent pending). I called it the Emulated Elastic Actuator after the Series Elastic Actuator.

The idea is to come up with a mechanism that has very low gear ratio, that is highly backdrivable, and has practically zero backlash and then use an electric motor, with a high-speed local control, to produce the required torque in every time instance to mimic the behaviour of a physical spring. The most important requirement is, the control to be local, in order to be able to realize high-speed operation (more than 20.000 iteration/sec). Until recently, the typical fastest torque control was in the range of 1-2 thousands of iteration per second, which is slower at least of one order.

In order to investigate the concept the detailed model of the system is given, including the model of the Hybrid Stepper Motor (HSM) and the model of the commutating electronics. I linearized the non-linear dynamics of the motor based on the position feedback. To support the theory of the concept, hardware implementation was designed and implemented.

Related chapter of the dissertation: III.2

2.2. By using the Hookean and the Kelvin-Voight elasticity model I have shown that the concept of the EEA can be used to mimic the behavior of a physical spring with linear characteristics. I also showed the feasibility of emulating positive or even negative damping.

With the help of the EEA concept, I have investigated two linear elastic behaviour. I have implemented the simple Hookean and the Kelvin-Voight models with different elasticity parameters. The latter is important for the reason that it incorporates damping along with the Hookean elasticity. The governing equation for rotational motion can be written as

$$\tau_{kv} = -k\Delta\theta_s - \eta\frac{d\theta_s}{dt}, \tag{1}$$

where τ_{kv} is the exerted torque due to spring and the damper, and the η is the viscosity (N m s/ rad) parameter. By selecting an η to be negative, the concept can go beyond the limits of the passive systems, featuring negative damping. Fig. 2.(a) shows the numerical simulation result with $k = 44.5$ N m/rad and $\eta = -1.28 \times 10^{-3}$ N m s / rad.

For validating the simulation results real hardware implementation was used to provide experimental measurements. It is depicted in Fig. 2.(b), that shows fine match with the previous simulations.

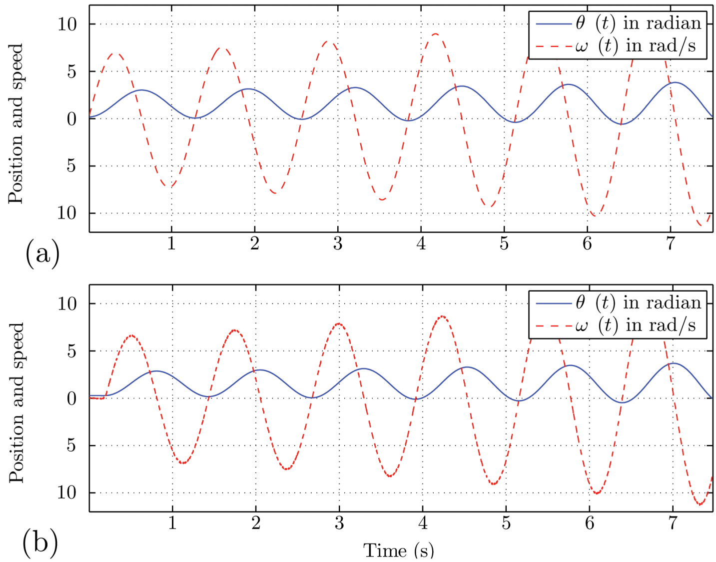

Figure 2: Side-by-side comparison of simulation (a) and experimental (b) results of the system emulating Kelvin-Voight elastic model with $k = 44.5$ Nm/rad and $\eta = -1.28 \times 10^{-3}$ N m s/rad.

. *Related chapter of the dissertation: III.4*

2.3. I extended the concept of the Emulated Elastic Actuator to non-linear elastic behavior. By constructing and modeling, with the Euler-Lagrange method, an underactuated one-legged robot I have demonstrated that, contrary to state-of-the-art compliant actuators, reconfigurable elasticity with non-linear characteristic can be efficiently realized with the help of the EEA.

It is a common approach to model our legs as springs [16,17]. During touch-down, the compression of the virtual spring imitates the behavior of the leg as it is trying to absorb the impact. Apparently, not only the human legs can be modeled as springs but the biped robot's as well. In order to realize even a simple linear virtual spring, non-linear elastic behavior is required at the joints, however, state-of-the-art compliant actuators are usually limited to linear elasticities.

In order to investigate the emulation of non-linear springs, I designed and implemented an underactuated, one legged robot with two degree of freedom. I used the energy based Euler-Lagrange method to formulate the dynamics of the robot. In order to realize the linear virtual spring a non-monotonic, non-linear elasticity is used

$$\tau_{ns} = -2k_{ns}l^2 \cos\left(\frac{\theta}{2}\right)\left[\sin\left(\frac{\theta_r}{2}\right) - \sin\left(\frac{\theta}{2}\right)\right], \qquad (2)$$

where the index $_{ns}$ denotes the non-linear spring, $\tau_{ns}(\theta)$ is the torque-deflection characteristic of the new torsional elasticity and θ_r is the resting angle. The result of the simulation was verified with hardware implementation that showed a fine match with the previous simulations.

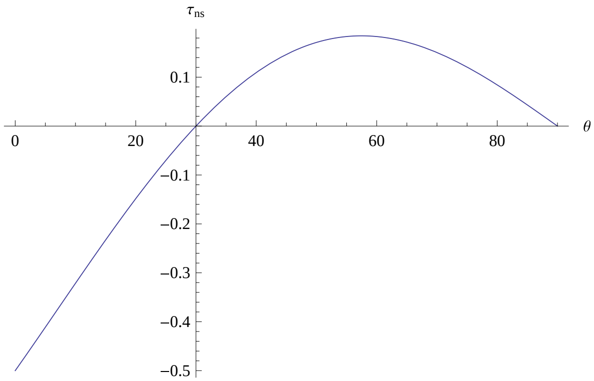

Figure 3: Non-linear torque-deflection characteristic $\tau_{ns}(\theta)$ of the joint elasticity intended to realize the desired linear virtual spring ($k_{ns} = 1, l = 1, \theta_r = 45°$).

Related chapter of the dissertation: III.5

4 Application of the results

During my work, all the algorithms and hardware realizations I designed give a possible solution for real and up to date problems.

The results of the first thesis group will hopefully offer a solution for creating high degree-of-freedom low-cost robotic joints with a reduced level of backlash. For example, for humanoid robots with 30 or more degree-of-freedom the result could be used to eliminate the need for expensive harmonic drives. Therefore, the proposed solution is highly recommended for moderate cost humanoid or legged robotic applications.

In terms of the second thesis group, the main application of the results would be dynamic legged robots. A new type of actuator is presented that could be a promising alternative of the Series Elastic Actuators. The novel actuator can be useful almost in any case where SEA is used. For example, in walking, hopping and running robots. Incorporating the EEA with humanoid robots could lead to an even better human-like motion.

In addition, the EEA could also be used in modern manipulators that extends the possible applications to industrial utilization. Industrial manipulators can be improved by further enhancing the safety of the co-working with humans. Additional applications could be found in the field of industry that could utilize the ability of the concept of mimicking elastic behavior. For example, in the service industry or in the automobile industry knobs with reprogrammable torque-deflection characteristic would be achievable (like the BMW iDrive, etc.).

5 Acknowledgement

First of all, I would like to thank my supervisor György Cserey for introducing me to scientific work and for his constant support in bringing our ideas into reality and believing in my research activity.

I am thankful for the Pázmány Péter Catholic University Faculty of Information Technology and the Multidisciplinary Doctoral School for providing tools and a caring environment for my work, especially personally for Judit Nyékyné-Gaizler, Tamás Roska and Péter Szolgay.

I would like to thank to my closest colleague Ákos Tar for the long-lasting joint work during these years. The cooperation of my colleagues at the Robotics Laboratory Ákos Gombkötő, Norbert Sárkány, Ádám Rák, Norbert Hóz, Balázs Jákli, Gergely Soós, Alpár Sándor and Ferenc Lombai is greatly acknowledged. The work with them greatly contributed to my scientific results. I would like to thank also my fellow PhD students and friends for their help, especially to Dávid Tisza, Péter Vizi, János Rudan, Zoltán Tuza, Dániel Szolgay, András Kiss, Gábor Tornai, László Füredi, Zoltán Kárász, Andrea Kovács, Vilmos Szabó, Kálmán Tornai, Balázs Varga, Tamás Pilissy, Róbert Tibold, Ádám Balogh and Endre László. Thanks especially for the discussions and ideas to Gábor Szederkényi, András Oláh, Attila Kis, Gábor Vásárhelyi, Kristóf Iván, Éva Bankó, Béla Weiss, Kristóf Karacs and Attila Tihanyi. Special credits are also for the endless patience and helpfulness to Mrs Vida, Lívia Adorján, Mrs Haraszti, Mrs Körmendy, Mrs Tihanyi and Mrs Mikesy and the rest of administrative and financial personnel. The Opera-

tional Program for Economic Competitiveness (GVOP KMA), The office of Naval Research (ONR) and the Hiteles Ember Foundation for their support are greatfully acknowledged. Special thanks go to Sarolta Tar, Miklós Gyöngy and Zsófia Cserey who helped a lot in the English revision of the text.

The loving support of all my family and my fiancée Zsófia helped me through the hardest moments of this period.

6 List of publications

6.1 Journal Publications of the Author

[1] B. Soós, Á. Rák, **J. Veres**, *and G. Cserey, "Gpu boosted cnn simulator library for graphical flow-based programmability,"* EURASIP Journal on Advances in Signal Processing*, vol. 2009, p. 8, 2009.*

[2] **J. Veres**, *G. Cserey, and G. Szederkényi, "Bio-inspired backlash reduction of a low-cost robotic joint using closed-loop-commutated stepper motors,"* Robotica*, vol. FirstView, pp. 1–8, 2013.*

6.2 Conference Publications of the Author

[3] Á. Tar and **J. Veres**, *"Design and realization of a biped robot using stepper motor driven joints," in* Mechatronics, 2006 IEEE International Conference on*, pp. 493–498, IEEE, 2006.*

[4] B. Soós, Á. Rák, **J. Veres**., *and G. Cserey, "Gpu powered cnn simulator (simcnn) with graphical flow based programmability," in* Cellular Neural Networks and Their Applications, 2008. CNNA 2008. 11th International Workshop on*, pp. 163–168, IEEE, 2008.*

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[6] *N. Sárkány, G. Cserey, Á. Tar, and* ***J. Veres****, "Design of a biomechatronic hand (bmt-h) actuated by the flexor-extensor mechanism," in* Advanced Intelligent Mechatronics (AIM), 2011 IEEE/ASME International Conference on*, pp. 446–450, IEEE, 2011.*

6.3 Patents of the Author

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[8] *Á. Tar,* ***J. Veres*** *and G. Cserey, "Érzékelő eszköz."* Hungarian Patent*, No. P1100633/1.*

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