Human-Like Model-Based Motion Generation Combining Feedforward and Feedback Control for Musculoskeletal Robots

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1 Introduction

In order to improve legged locomotion of robots, both actuation and control challenges need to be tackled. In the last decade, compliant actuation has been identified as an important key towards natural motion performance [1]. Understanding the mechanisms and principles underlying human motion guides various research projects today to develop robotic legs that are close to the functionalities of the human musculoskeletal system.

Steps towards human-like musculoskeletal robotic legs were made in [2, 3, 4]. Hosoda et al. developed a pneumatically driven monopod with the main nine muscle groups involved in human locomotion (cf. Fig. 1a) to investigate biomechanical findings during jumping [2]. The robot Lucy was equipped with antagonist-agonist monoarticular muscle pairs to realize slow walking motions [3]. Niiyama et al. developed motor control for jumping and landing of a pneumatically actuated biped with biarticular muscles for jumping [4]. While, with respect to the long-term goal of energy-efficient and mobile bipedal robots, the use of pneumatics is not recommended, the positive effects of monoarticular and biarticular muscle groups have been emphasized in several biomechanical studies [5, 6, 7].

The BioBiped project [8] aims at the realization of human like jogging and walking abilities with musculoskeletal three-segmented legs using tendon driven series elastic actuation [9]. We are convinced that muscle-tendon like structures offer tremendous potential for legged locomotion that yet needs to be fully investigated by developing well elaborated simulation models and hardware platforms.

2 Contributions

So far, two prototypes with three-segmented elastic legs, BioBiped1 (cf. Fig. 1c) and BioBiped2, have been built in this project by using different actuation types including mono- and biarticular structures. Both prototypes have rotational hip, knee and ankle joints and a simple trunk for stabilization purposes.

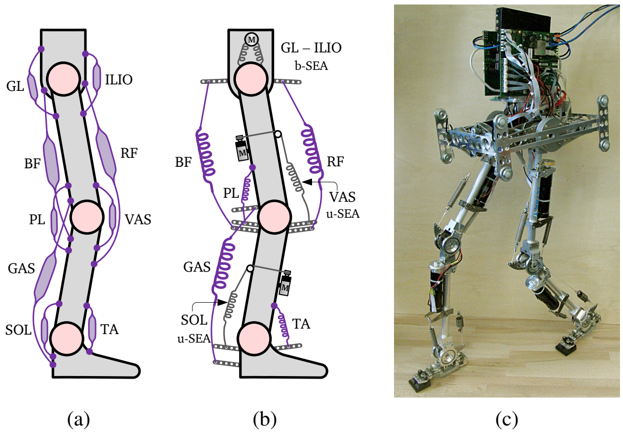
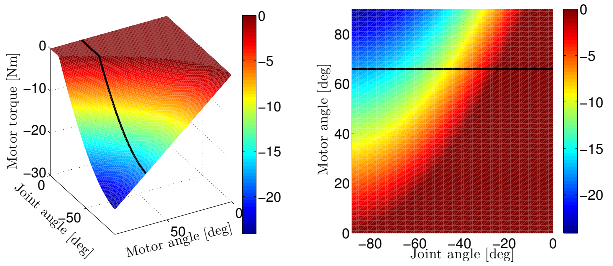


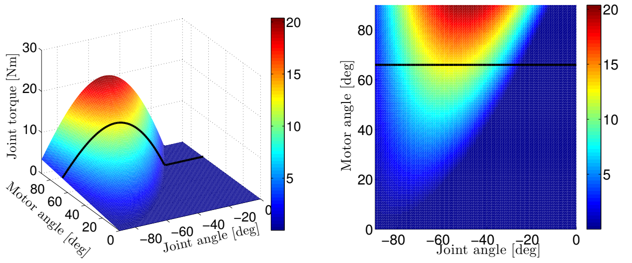
Figure 1: Technical realization of the BioBiped actuation system: (a) Main muscle groups in human legs, (b) technical realization of the bi- and unidirectional elastic structures in the legs of BioBiped1, (c) real BioBiped1 platform.

The integrated actuation types are studied thoroughly during dynamic motions such as hopping and jogging. We differentiate between two types of bidirectional and unidirectional series elastic actuators (b-SEA & u-SEA) consisting of an electrical direct-current motor that is connected via a Dyneema tendon with built-in extension spring to a joint. The knee and ankle joints are each actuated by a combination of a u-SEA and its passive counterpart. In addition, each leg has three passive biarticular structures that connect two joints. b-SEAs are used only for the actuation of the hip joints. The technical realization scheme of these actuators is depicted in Fig. 1b.

Using only experiments to understand BioBiped's movement dynamics has fundamental drawbacks. In order to systematically identify the contribution of each structure to the overall leg dynamics, it is necessary to study the robot's detailed multi-body system (MBS) dynamics model. The MBS model needs to capture the dynamics of the active/passive series-elastic, mono- and biarticular structures and to provide realistic contact dynamics, as described in [10]. We will present the working principles and models of the various actuator types in terms of mathematical models and analyze the output torque functions. The characteristic curves are highly nonlinear and depend on several parameters. The diagrams in Fig. 2 display the motor and joint torques induced by the u-SEA VAS in its workspace. As shown in Fig. 3, the curves are different for varying attachment points.



(a) Motor torques (b) Motor torques (top view)



(c) Joint torques (d) Joint torques (top view)

Figure 2: Motor torques induced by the monoarticular u-SEA VAS in the view from the front (a) and from the top (b) for rest angle $q_0 = -90°$, motor positions $\theta = [0, 90°]$, joint positions $q = [-90°, 0]$ and attachment point number 5 (AP 5). Joint torques generated by VAS for the same setting in the front view (c) and top view (d). The black line represents the curves at motor angle $\theta = 66°$ (cf. Fig. 3). In flat areas slacking of the tendon occurs.

These complex actuation dynamics raise the question of suitable controllers that take into consideration the mechanical structure of the robot. Desired locomotion trajectories can be either obtained from capturing human motion or computer generated. Referring to the main hypothesis of the BioBiped project, that the central humanoid locomotion ability should be jogging, emphasis lies on analyzing fast dynamic motions that are given by means of joint angles.

Deriving the motor torques includes the computation of the actuated joint torques first. However, floating base inverse dynamics control is an ill-posed problem. Therefore, we split up the computation of the simulated robot's inverse dynamics into several smaller steps without the need for actually computing directly the inverse dynamics of the elastic system. An overview is given in Fig. 4.

Independent of the specific actuation, we first compute the forward dynamics of a rigid robot without any elasticities based on the time-varying joint reference trajectories $q_{\mathrm{d}}(t)$. A classical PD controller determines the required joint torques, denoted as τ_{st}, to move the rigid robot model along the desired motion trajectories, which are specified in joint coordinates, starting from measurements of the current joint states $q_{\mathrm{st}}(t)$ during the forward dynamics computation. The outcomes of this step, $\tau_{\mathrm{st}}(t)$ and $q_{\mathrm{st}}(t)$, are used in the next step to analytically determine the motor angles and torques, $\theta(t)$ and $\tau_{\mathrm{m}}(t)$, for the elastic robot based on the corresponding models of the actuation structures. In this last step the forward dynamics of the elastic robot, including its actuation, is computed. Each actuator is PD controlled to track the precomputed motor positions θ_{c}. The PD controller can be enhanced to also track the desired joint positions $q_{\mathrm{d}}(t)$. An important component of this controller represents the feedforward compensation by utilizing the computed torques $\tau_{\mathrm{mc}}(t)$. Provided the correctness of the joint torques and positions obtained for the rigid joint-link structure and that of the actuator models the feedforward term reduces immensely the controller efforts.

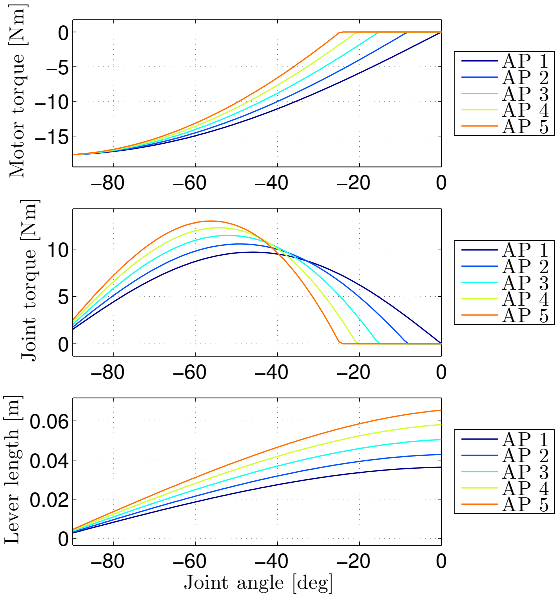


Figure 3: Motor torques, joint torques and lever lengths for the same settings as in Fig. 2 for all attachment points, abbreviated as AP in the legends above, when the motor is fixed at $\theta = 66°$. The black line in all diagrams from Fig. 2 is equal to the curve "AP 5" in the corresponding diagrams of the joint and motor torques.

In [11] we had applied this method to a robot solely actuated by b-SEAs in each leg joint with the dimensions of the BioBiped robot and demonstrated successful simulations of human jogging and computer-generated hopping motions. For a robot driven by b-SEAs the computation of the motor angles and torques is rather simple, as the b-SEA describes a linear transmission relation. This approach has been now expanded to take into account the highly nonlinear dynamics of the passive monoarticular/biarticular structures and of the active u-SEAs in each knee and ankle joint.

3 Discussion

Our investigations and results target at answering questions from three important areas: actuation, control, and biomechanical gait analyses. As for the first part, we deal with the question what kind of actuation systems are required for improved locomotion performance. What can be gained by human-like muscle-tendon structures as realized in the BioBiped prototypes? Is the operation range of these struc-

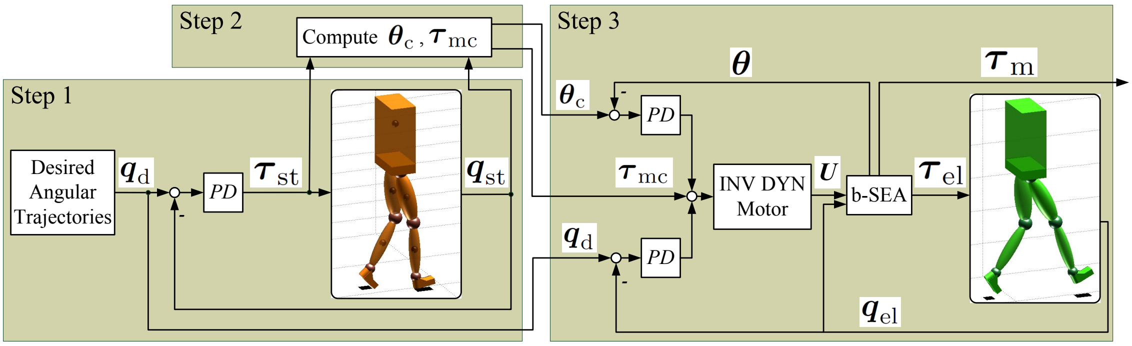


Figure 4: Successive steps from 1 to 3 to determine the required motor control signals [11].

tures in terms of adjustment possibilities sufficient for significantly improved energy-efficient motions? The results allow to derive helpful design guidelines for the next, further improved prototypes planned within the BioBiped project.

As for the control part, we ask the question how to design controllers that utilize best the specific mechanical features of the actuation system. We propose a method that has already been applied successfully to a simulated robot driven by b-SEAs in each leg joint [11] and that has been recently extended to take into account the actuator types introduced above.

Related to the last question, we would like to discuss the following question: What are the main features of human-like motion performance that are desirable to be realized by robots? Further, how can these features be embodied and how are they related to each other?

Format: Poster with animations presented on personal laptop

Keywords: Musculoskeletal system, compliant actuation, model-based control, hopping

References

[1] R. V. Ham, T. Sugar, B. Vanderborght, K. Hollander, D. Lefeber, “Compliant actuator designs,” *IEEE Robot. Automat. Mag.*, vol. 16, no. 3, pp. 81–94, 2009.

[2] K. Hosoda, Y. Sakaguchi, H. Takayama, T. Takumai, “Pneumatic-driven jumping robot with anthropomorphic muscular skeleton structure,” *Autonomous Robots*, vol. 28, no. 3, pp. 307–316, 2010.

[3] B. Verrelst, R. V. Ham, B. Vanderborght, F. Daerden, D. Lefeber, and J. Vermeulen, “The pneumatic biped “Lucy” actuated with pleated pneumatic artificial muscles,” *Autonomous Robots*, vol. 18, no. 2, pp. 201–213, 2005.

[4] R. Niiyama, A. Nagakubo, and Y. Kuniyoshi, “Mowgli: A bipedal jumping and landing robot with an artificial musculoskeletal system,” in *IEEE Int. Conf. on Robotics and Automation*, pp. 2546–2551, 2007.

[5] G. J. van Ingen Schenau, M. F. Bobbert, and R. H. Rozendal, “The unique action of bi-articular muscles in complex movements,” *Journal of Anatomy*, vol. 155, pp. 1–5, 1987.

[6] R. Jacobs, M. F. Bobbert, and G. J. van Ingen Schenau, “Mechanical output from individual muscles during explosive leg extensions: The role of biarticular muscles,” *Journal of Biomechanics*, vol. 29, no. 4, pp. 513–523, 1996.

[7] A. J. van den Bogert, “Exotendons for assistance of human locomotion,” *BioMedical Engineering OnLine*, vol. 2, no. 17, 2003.

[8] Biobiped project website. [Online]. Available: `http://www.biobiped.de`

[9] K. Radkhah, C. Maufroy, M. Maus, D. Scholz, A. Seyfarth, O. von Stryk, “Concept and design of the BioBiped1 robot for humanlike walking and running,” *Int. J. of Humanoid Robotics*, vol. 8, no. 3, pp. 439–458, 2011.

[10] T. Lens, K. Radkhah, and O. von Stryk, “Simulation of dynamics and realistic contact forces for manipulators and legged robots with high joint elasticity,” in *Int. Conf. on Advanced Robotics*, pp. 34–41, 2011.

[11] K. Radkhah, O. von Stryk, “Actuation requirements for hopping and running of the musculoskeletal robot BioBiped1,” *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 4811–4818, 2011.