27/28th International Conference
ENGINEERING MECHANICS 2022
Milovy, Czech Republic, May 9 –12, 2022
Paper **#40,** pp. 309–312, doi: 10.21495/51-2-309

ON THE DESIGN AND MODELING OF A TRAINER FOR THE UNDERACTUATED WALKING ROBOT WITHOUT ANKLES

Polach P.[*], Anderle M.[**], Papáček Š.[***]

Abstract: *The purpose of this paper is to present a preliminary design and kinematic analysis of a simple mechanical device, called the trainer. This experimental device is designed for future use in a mechatronic system being the five-link laboratory walking-like system. The experiments on the trainer planned for the near future, aim to validate the recently developed controller implementation in the real underactuated walking robot model. Yet, the preliminary results demonstrate the suitability of the proposed trainer device.*

Keywords: **Mechatronics, Walking robot, Multibody dynamics, Computer simulations, Control applications.**

1. Introduction

The aim of this paper is to make a move towards the design and modeling of a simple mechanical device, called further the trainer (the term *trainer* has been found as the best translation of the Czech word *"trenažér"*) to run experiments related to the implementation of the previously developed sensor and control algorithms for the real-time movement of the laboratory walking robot, see Fig. 1 (right). The detailed description of this underactuated walking-like mechanical system (called further UTIA Walking Robot – UWR), being developed and built at the Department of Control Theory of the Institute of Information Theory and Automation (UTIA), Czech Academy of Sciences, is provided by Anderle and Čelikovský (2019) and Anderle et al. (2015).

2. Preliminaries

The underactuated mechanical system (i.e. the system has fewer actuators than degrees of freedom) includes many applications in different fields, e.g., in robotics, in aeronautical and spatial systems, in marine and underwater systems, and in-flexible and mobile systems, see (Krafes et al., 2018). The simplest underactuated walking robot hypothetically able to walk is the so-called Compass gait biped walker, alternatively called the Acrobot. There are two degrees of freedom mechanism for one pair of legs without knees, ankles and feet actuated only in the hips. Moreover, an additional (third) link is representing the pelvis in the human body description (or a torso), see Fig. 1 (left). The extension towards more realistic walking requires the addition of knees into Acrobot legs resulting in the so-called four-link walking-like mechanical system, see Fig. 1 (middle and right).

Although there are numerous advantages of underactuated mechanical systems, e.g. reduction of weight, the energy cost of the reduced control, these systems usually exhibit a highly nonlinear dynamic and their control is a very challenging task. Let us emphasize that none of the techniques proposed and developed for fully actuated systems, e.g. robots, can be applied directly to any underactuated mechanical system.

---

[*] Assoc. Prof. Dr. Ing. Pavel Polach: Research and Testing Institute Plzen Ltd.; Tylova 1581/46, 301 00 Plzen; CZ, polach@vzuplzen.cz

[**] Ing. Milan Anderle, PhD.: The Czech Academy of Sciences, Institute of Information Theory and Automation; Pod vodárenskou věží 4, 182 08 Prague; CZ, anderle@utia.cas.cz

[***] Assoc. Prof. Ing. Štěpán Papáček, PhD.: The Czech Academy of Sciences, Institute of Information Theory and Automation; Pod vodárenskou věží 4, 182 08 Prague; CZ, papacek@utia.cas.cz

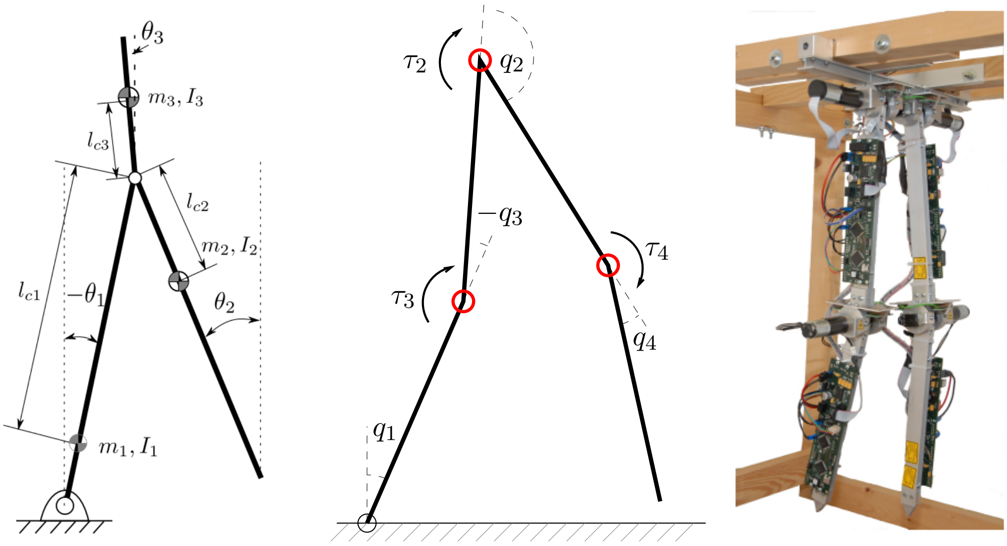

Fig. 1: (left) Compass gait biped walker. (middle and right) UTIA Walking Robot: four-link laboratory mechatronic walking robot-like system – in fact, there are 4 + 1 links, where "plus one" means a torso – still immobile.

Despite the fact that the control inputs can only partially control the dynamics, using suitable techniques, the coordinates of the internal dynamics can be controlled indirectly.

The general-purpose computer-based discipline known as multibody systems analysis is widely used in various branches of engineering. We used multibody modelling in the design and development of a trainer for the real-time movement of the laboratory walking robot. The mathematical models, created using specialized software, are mostly the sets of nonlinear differential and algebraic equations (DAEs). It is sometimes more advantageous to formulate and to solve the equations of motion of a studied multibody system without the usage of commercial software tools. The main reason is the limited possibility of introducing some special features and special model elements as well as some non-standard solution or optimization methods, see, e.g. ,(Hajžman and Polach, 2007) and references therein. The Alaska 2021 (2021) simulation tool is used for creating a multibody model of the UWR. The older version of the Alaska simulation tool, see, e.g., Maißer et al. (1998), is not a typical commercial software, but rather a programming tool based on a programming language that supports the creation of multibody models and simulations with them.

3. Control of the trainer

The approach to control the Acrobot based on the partial feedback linearization method from (Čelikovský et al., 2008), can be extended and used to control the more realistic underactuated walking robots, e.g. the 3-link or the 4-link as depicted in Fig. 1. The extension is based on the method of embedding the Acrobot into the more sophisticated underactuated mechanical system such that the actuator between the legs is controlled as it would be the Acrobots angle whereas the remaining actuators, i.e. in the knees and/or in the torso, are controlled according to the predefined constraining functions. Details can be found in (Čelikovský et al., 2013). The outputs of both the partial feedback linearization based algorithm and the constraining enforcement algorithm are torques to be applied at the corresponding joints to enforce the required movement, in our case the walking like movement (as can be seen in Fig. 2 left). Classical Euler-Lagrange modelling approach of the 4-link schematically depicted in Fig. 1 (middle) leads to a differential equation in the well-known form for the mechanical systems including the inertia matrix, the Coriolis and the centrifugal forces matrix and the gravity vector. A mathematical software, e.g. the MATLAB, can be used to simulate the movement control of the 4-link according to the control law. The result of the simulation can be seen in Fig. 2 (right). Nevertheless, our aim is to verify the control approach using the real underactuated walking robot. To do so, the trainer is necessary to build and use. Even though the geometry and mass distribution of the real walking robot was taken into the account during the 4-link modelling using the Euler-Lagrange approach, the trainer and its influence on the walking robot is difficult to include into

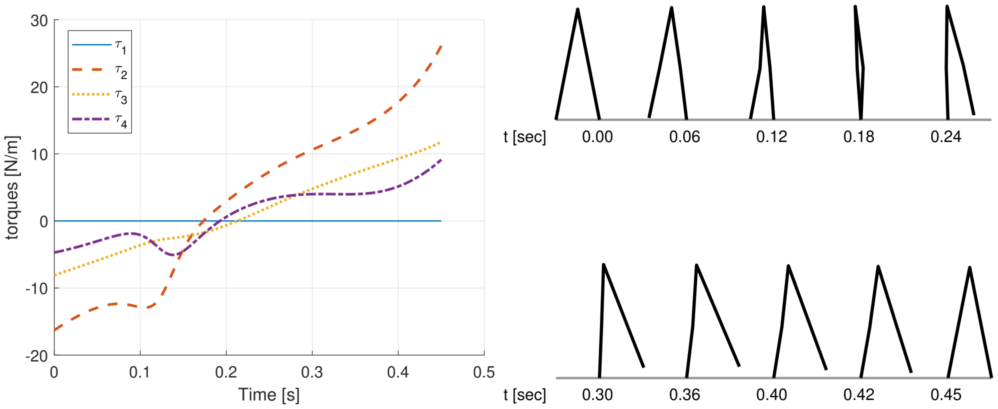

Fig. 2: (left) Courses of required torques. (right) Single step animation of underactuated walking of the 4-link.

the model and simulate its influence. For this reason, the Alaska multibody dynamics software will be used to simulate the step of the robot with the trainer according to precomputed torques.

4. Design and analysis of the trainer system for the UTIA Walking Robot

The real (physical) model of the underactuated UWR shown in Fig. 1 (right) consists of four links that form two legs with knees, each knee is equipped with the DC motor. Both legs are connected to the hip via two joints, each equipped with a DC motor as well. Each link of the robot is equipped with sensors for angular position and velocity measurement and DC motor input current measurement. In order to advance from the merely *in silico* simulations of the controller implementation to the real experiments on the UWR – real physical system, we aim to design a simple mechanical device, the already mentioned *trainer – trenažér*, and eventually run the real walking robot with the help of such device. The UWR is consisting of two legs with knees composed together with the torso at the hips. Moreover, in order to impose the planar motion, a planar joint between the torso (with the hips) and the immobile ground – base (a vertical wall) is included (see the planar joint in Fig. 3).

Further, we deal with the kinematic analysis of the trainer system for the UWR. Nevertheless, although the UWR motion is being developed in parallel planes, i.e., the system under study is a planar mechanism, the subsequent analysis is done in 3D space. The reason for this apparently more complicated choice resides in the possibility to model all reactions in 3D (mainly the normal reaction in the planar join and the contact forces between the UWR and the moving belt).

In the multibody model of the UTIA Walking Robot integrated with the trainer, created in the Alaska simulation tool, they are, in this stage of model development, the structural parts of the UWR modeled as rigid bodies. The number of degrees of freedom in kinematic joints of the UWR multibody model is 7. There is the planar joint between the body 4 (the body 4 corresponds with the pelvis in human body description) and the base 1 (vertical wall), the revolute joint between the body 4 and bodies 3 (right thigh in the human body) and 5 (left thigh in the human body), the revolute joint between the body 3 and 2 (left lower leg in the human body) and the revolute joint between the body 5 and 6 (right lower leg in the human body) are considered. The joint variables in the kinematic joint are prescribed and optimized. The contact conditions in the connection "sole" of the UWR and moving belt are modeled using the barrier functions and spring-damper elements.

5. Conclusion and outlook

This work represents the first step in designing a trainer device enabling to validate the previously developed sensor and control algorithms for the real-time movement of biped walking robots. Following the successful kinematic analysis, the analysis of system dynamics in the Alaska simulation tool is conceived. While the kinematic joints impose the planar motion of the walking robot, we do not ignore the third (lateral) dimension, having the possibility to simulate respective forces, mainly reactions between robot and lateral wall (immobile base 1) in the planar joint, for previously defined motions of the actuated links. Special

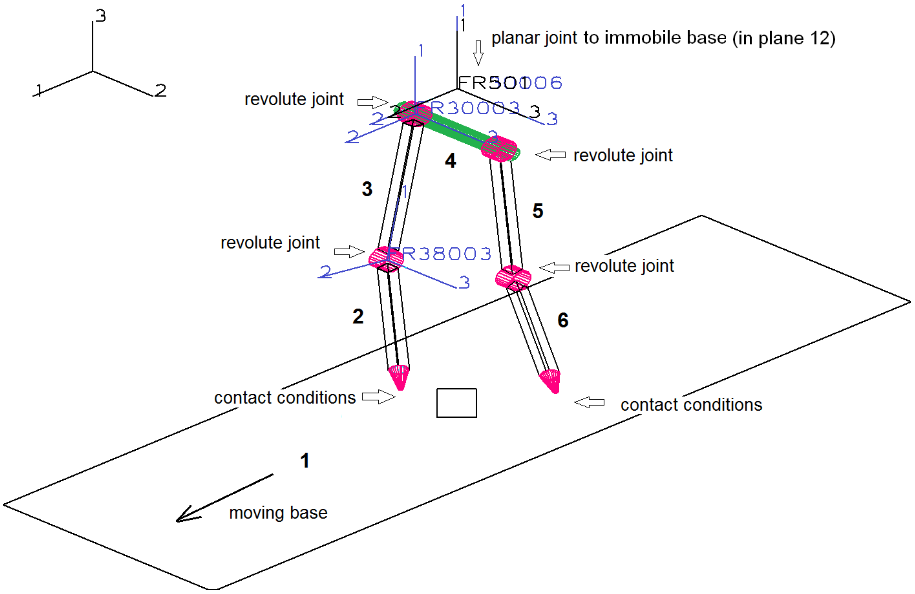

Fig. 3: Visualization of the UTIA Walking Robot (with the description of kinematic joints) walking on the moving belt (treadmill) and supported by a planar joint using Alaska 2.3 simulation tool.

attention is paid to searching for a specific, in some sense optimal, realisation of the planar joint as well as the ideal distribution of the torque to be applied between the legs into two actuators placed at the hip of the real walking robot. As this is the first stage of the project solution, a model of the underactuated robot was built in the Alaska simulation tool whereas the simulations of walking with the trainer support are left for future publication.

Inspired by the work of Čelikovský et al. (2008), our ongoing research concerns numerical simulations for testing the ability of various feedback methods to stabilize the robot in a certain equilibrium. Consequently, equipped by both the dynamic multibody model and the selected control algorithms, an optimization problem residing in minimization of required torques can be formulated and solved for certain mechanical parameters, e.g. mass of the links, as arguments of the optimization problem.

Acknowledgements

The work of Pavel Polach was originated in the framework of institutional support for the long-time conception development of the research institution provided by the Ministry of Industry and Trade of the Czech Republic to Research and Testing Institute Plzen. The work of Milan Anderle and Štěpán Papáček was supported by the Czech Science Foundation through the research grant project No. 21-03689S.

References

Alaska 2021 (2021), *alaska Reference Manual Release 2021.1*, Institut für Mechatronik e. V., Chemnitz.

Anderle, M. and Čelikovský, S. (2019), On the controller implementation in the real underactuated walking robot model. In: *Proc. 12th Asian Control Conference (ASCC)*, Kitakyushu, Fukuoka, Japan, June 2019, pp 91-99.

Anderle, M., Čelikovský, S., Dolinský, K. (2015), Simple model of underactuated walking robot. In: *Proc. 10th Asian Control Conference (ASCC)*, Kota Kinabalu, Malaysia, May 2015, pp 2131-2136.

Čelikovský, S., Anderle, M., Moog, C. (2013), Embedding the generalized Acrobot into the n-link with an unactuated cyclic variable and its application to walking design. In: *Proc. European Control Conference (ECC)*, Zurich, Switzerland, July 2013, pp 682-689.

Čelikovský, S., Zikmund, J., Moog, C. (2008), Partial exact linearization design for the Acrobot walking. In: *Proc. American Control Conference (ACC)*, Seattle, USA, June 2008, pp 874-879.

Hajžman, M. and Polach, P. (2007), Application of stabilization techniques in the dynamic analysis of multibody systems. *Applied and Computational Mechanics*, Vol 1, pp 479-488.

Krafes, S., Chalh, Z. and Saka, A. (2018), A Review on the Control of Second Order Underactuated Mechanical Systems. *Complexity*, Vol 2018, Article ID 9573514, 17 pp.

Maißer et al. (1998), *alaska, User Manual, Version 2.3*, Institut für Mechatronik e. V., Chemnitz.