52. IWK

Internationales Wissenschaftliches Kolloquium
International Scientific Colloquium

PROCCEDINGS | **10 - 13 September 2007**

FACULTY OF COMPUTER SCIENCE AND AUTOMATION

COMPUTER SCIENCE MEETS AUTOMATION

VOLUME I

Session 1 - Systems Engineering and Intelligent Systems
Session 2 - Advances in Control Theory and Control Engineering
Session 3 - Optimisation and Management of Complex Systems and Networked Systems
Session 4 - Intelligent Vehicles and Mobile Systems
Session 5 - Robotics and Motion Systems

TECHNISCHE UNIVERSITÄT
ILMENAU

Bibliografische Information der Deutschen Bibliothek
Die Deutsche Bibliothek verzeichnet diese Publikation in der deutschen Nationalbiografie; detaillierte bibliografische Daten sind im Internet über **http://dnb.ddb.de** abrufbar.

ISBN 978-3-939473-17-6

Impressum

Herausgeber:
Der Rektor der Technischen Universität Ilmenau
Univ.-Prof. Dr. rer. nat. habil. Peter Scharff

Redaktion:
Referat Marketing und Studentische Angelegenheiten
Kongressorganisation
Andrea Schneider
Tel.: +49 3677 69-2520
Fax: +49 3677 69-1743
e-mail: kongressorganisation@tu-ilmenau.de

Redaktionsschluss: Juli 2007

Verlag:
Technische Universität Ilmenau/Universitätsbibliothek
Universitätsverlag Ilmenau
Postfach 10 05 65
98684 Ilmenau
www.tu-ilmenau.de/universitaetsverlag

Herstellung und Auslieferung:
Verlagshaus Monsenstein und Vannerdat OHG
Am Hawerkamp 31
48155 Münster
www.mv-verlag.de

Layout Cover: www.cey-x.de

Bezugsmöglichkeiten:
Universitätsbibliothek der TU Ilmenau
Tel.: +49 3677 69-4615
Fax: +49 3677 69-4602

Preface

Dear Participants,

Confronted with the ever-increasing complexity of technical processes and the growing demands on their efficiency, security and flexibility, the scientific world needs to establish new methods of engineering design and new methods of systems operation. The factors likely to affect the design of the smart systems of the future will doubtless include the following:

- As computational costs decrease, it will be possible to apply more complex algorithms, even in real time. These algorithms will take into account system nonlinearities or provide online optimisation of the system's performance.
- New fields of application will be addressed. Interest is now being expressed, beyond that in "classical" technical systems and processes, in environmental systems or medical and bioengineering applications.
- The boundaries between software and hardware design are being eroded. New design methods will include co-design of software and hardware and even of sensor and actuator components.
- Automation will not only replace human operators but will assist, support and supervise humans so that their work is safe and even more effective.
- Networked systems or swarms will be crucial, requiring improvement of the communication within them and study of how their behaviour can be made globally consistent.
- The issues of security and safety, not only during the operation of systems but also in the course of their design, will continue to increase in importance.

The title "Computer Science meets Automation", borne by the 52nd International Scientific Colloquium (IWK) at the Technische Universität Ilmenau, Germany, expresses the desire of scientists and engineers to rise to these challenges, cooperating closely on innovative methods in the two disciplines of computer science and automation.

The IWK has a long tradition going back as far as 1953. In the years before 1989, a major function of the colloquium was to bring together scientists from both sides of the Iron Curtain. Naturally, bonds were also deepened between the countries from the East. Today, the objective of the colloquium is still to bring researchers together. They come from the eastern and western member states of the European Union, and, indeed, from all over the world. All who wish to share their ideas on the points where "Computer Science meets Automation" are addressed by this colloquium at the Technische Universität Ilmenau.

All the University's Faculties have joined forces to ensure that nothing is left out. Control engineering, information science, cybernetics, communication technology and systems engineering – for all of these and their applications (ranging from biological systems to heavy engineering), the issues are being covered.

Together with all the organizers I should like to thank you for your contributions to the conference, ensuring, as they do, a most interesting colloquium programme of an interdisciplinary nature.
I am looking forward to an inspiring colloquium. It promises to be a fine platform for you to present your research, to address new concepts and to meet colleagues in Ilmenau.

Ch. Ament

Professor Peter Scharff
Rector, TU Ilmenau

Professor Christoph Ament
Head of Organisation

Table of Contents

CONTENTS

Page

1 Systems Engineering and Intelligent Systems

2 Advances in Control Theory and Control Engineering

3 Optimisation and Management of Complex Systems and Networked Systems

4 Intelligent Vehicles and Mobile Systems

5 Robotics and Motion Systems

Paper submitted after copy deadline

2 Advances in Control Theory and Control Engineering

52^{nd} Internationales Wissenschaftliches Kolloquium
Technische Universität Ilmenau
10 – 13 September 2007

C. Behn / K. Zimmermann

Biologically inspired Locomotion Systems and Adaptive Control

GENERAL APPROACH TO WLLS

In this paper we discuss the problem of developing worm-like locomotion systems (WLLS), which have the earthworm as a living prototype. Non-pedal forms of locomotion show many advantages and are very interesting in current robotic research. The following is taken as the basis of our theory:
(i) a worm is a terrestrical locomotion system of one dominant linear dimension with no active legs nor wheels; *(ii)* global displacement is achieved by (periodic) change of shape (such as local strain) and interaction with the environment; *(iii)* the model body of a worm is a 1-dimensional continuum that serves as the support of various fields.
The continuum in (iii) is just an interval of a body-fixed coordinate. Most important fields are: *mass,* continuously distributed (with a density function) or in discrete distribution (chain of point masses), *actuators*, i.e., devices which produce internal displacements or forces thus mimicking muscles, *surface structure* causing the interaction with the environment.

Observing the locomotion of worms one recognizes first a surface contact with the ground. It is well known, that, if there is contact between two bodies (worm and ground), there is some kind of friction, which depends on the physical properties of the surfaces of the bodies. In particular, the friction may be anisotropic (orientation dependent of the relative displacement). This interaction (mentioned in (ii)) could emerge from a surface texture as asymmetric Coulomb friction or from a surface endowed with scales or bristles (we shall speak of *spikes* for short) preventing backward displacements. It is responsible for the conversion of (mostly periodic) internal and internally driven motions into a change of external position (undulatory locomotion [5]), see [6] and [9].

Summarizing, we consider a WLLS in form of a chain of point masses in a common straight line (**a discrete straight worm**), which are connected consecutively by linear visco-elastic elements, see [1], [2], [9] for instance and Fig. 1.

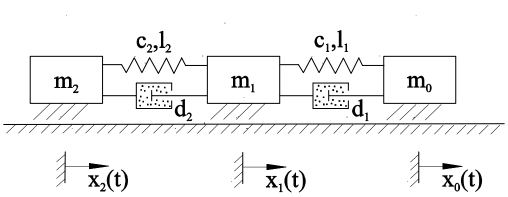

Fig. 1. Model of a WLLS - chain of point masses

In [6] and [7] the case is considered, where the point masses are endowed with scales, which could make the friction also orientation dependent (in sliding forward the frictional forces are minimal while in opposite direction the scales dig in and cause large friction). But, due to [1] and [2], we do not want to deal with reactive forces, we model this ground interaction as impressed forces - asymmetric (anisotropic) dry friction as a Coulomb sliding friction force.

WLLS AS A DYNAMICAL CONTROL SYSTEM

We model the ground interaction as an **asymmetric Coulomb dry friction force** F, which is taken to be different in the magnitude depending on the direction of each point mass motion:

$$\dot{x} \mapsto F(\dot{x}) = \begin{cases} -F^{+} & , \dot{x} > 0 \\ F^{0} & , \dot{x} = 0 \\ F^{-} & , \dot{x} < 0 \end{cases} \tag{1}$$

where $F^{+}, F^{-} > 0$ are fixed with $F^{-} >> F^{+}$ and F^{0} is arbitrary , $F^{0} \in \left(F^{-}, -F^{+}\right)$ (neglecting stick-slip). For later simulation we restrict the number of point masses to $n = 2$, but we point out that our theory is valid for fixed but arbitrary $n \in N$, see [3].

Mathematical model

Firstly, we derive the differential equations of motion of the WLLS by using Newton's second law:

$$\begin{aligned} m_0\ddot{x}_0 &= -c_1(x_0 - x_1) - d_1(\dot{x}_0 - \dot{x}_1) + F_0(\dot{x}_0) + u_1(t) \\ m_1\ddot{x}_1 &= \begin{cases} -c_1(x_1 - x_2) + c_2(x_0 - x_1) - d_1(\dot{x}_1 - \dot{x}_2) + d_2(\dot{x}_0 - \dot{x}_1) \\ \quad + F_1(\dot{x}_1) + u_2(t) - u_1(t) \end{cases} \\ m_2\ddot{x}_2 &= c_2(x_1 - x_2) + d_2(\dot{x}_1 - \dot{x}_2) + F_2(\dot{x}_2) - u_2(t) \end{aligned} \tag{2}$$

with $x_0(0) = x_{00},\ x_1(0) = x_{10},\ x_2(0) = x_{20},\ \dot{x}_0(0) = x_{01},\ \dot{x}_1(0) = x_{11},\ \dot{x}_2(0) = x_{21}$ (all initial values are real numbers). Putting

$$u_1 := c_1\, l_1 \text{ and } u_2 := c_2\, l_2 \tag{3}$$

then u_{ij} is in fact a control of the original spring length. Therefore, we have *internal* inputs and no longer external force inputs, as in [1]. New outputs of this system could be the actual distances of the point masses

$y_1 := x_0 - x_1$ and $y_2 := x_1 - x_2$. (4)

Therefore, this system (2), (4) is described by a mathematical model that falls into the category of quadratic, nonlinearly perturbed, minimum phase, multi-input $u(\cdot)$, multi-output $y(\cdot)$ systems with strict relative degree two.

Control objective

For the further analysis we suppose that the masses are all equal, but unknown, also the damping factors and spring stiffnesses, and the friction magnitudes as well (**uncertain systems**). The consideration of uncertain systems leads to the use of adaptive control. The aim is to design universal adaptive controllers, which learn from the behavior of the system, so automatically adjust their parameters and achieve a pre-specified control objective. Precisely, given an arbitrarily small $\lambda > 0$, a control strategy $y \mapsto u$ is sought which, when applied to the system, achieves λ-tracking for every reference signal $y_{ref}(\cdot)$ (belonging to a certain function class, for instance a given favoured kinematic gait presented), i.e., the following:

- every solution of the closed-loop system is defined and bounded on $R_{\geq 0}$, and
- the output $y(\cdot)$ tracks $y_{ref}(\cdot)$ with asymptotic accuracy quantified by $\lambda > 0$ in the sense that $\max\{0, \|y(t) - y_{ref}(t)\| - \lambda\} \to 0$ as $t \to +\infty$.

The last condition means that the error $e(t) := y(t) - y_{ref}(t)$ is forced, via the adaptive feedback mechanism (controllers (5) and (6)), towards a ball around zero radius $\lambda > 0$, see Fig. 2.

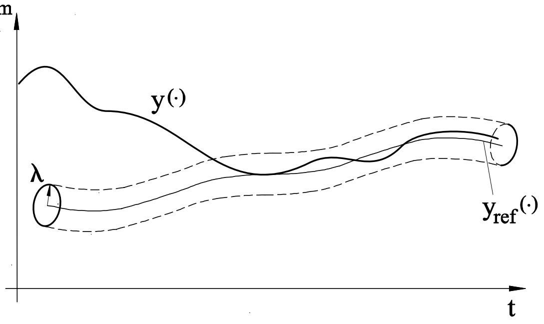

Fig. 2. The λ-radius around the reference signal

Controllers

Let us consider the following two λ-trackers, see also [1].

$$\left.\begin{array}{lcl} e(t) & := & y(t)-y_{ref}(t) \\ u(t) & = & -\left(k(t)\,e(t)+\frac{d}{dt}[k(t)\,e(t)]\right) \\ \dot{k}(t) & = & \left(\max\{0,\,\|e(t)\|-\lambda\}\right)^2 \end{array}\right\} \qquad (5)$$

with $k(0)=k_0\in R$, $\lambda>0$, $y_{ref}(\cdot)\in W^{2,\infty}$ (a Sobolev-Space), $u(t),\,e(t)\in R^2$ and $k(t)\in R$. The second one includes a dynamic compensator due to a controller of [4]. This controller allows us to avoid the drawback of using the derivative of the output:

$$\left.\begin{array}{lcl} e(t) & := & y(t)-y_{ref}(t) \\ u(t) & = & -\left(k(t)\,\vartheta(t)+\frac{d}{dt}[k(t)\,\vartheta(t)]\right) \\ \dot{\vartheta}(t) & = & -k(t)^2\,\vartheta(t)+k(t)^2\,e(t) \\ \dot{k}(t) & = & \left(\max\{0,\,\|e(t)\|-\lambda\}\right)^2 \end{array}\right\} \qquad (6)$$

with $\theta(0)=\vartheta_0$, $k(0)=k_0>0$, $\lambda>0$, $y_{ref}(\cdot)\in W^{2,\infty}$, $u(t),\,e(t),\,\vartheta(t)\in R^2$ and $k(t)\in R$. We stress, that the controller (6) does not invoke any derivatives. The structure of the feedback law and the simple adaptation law of the controllers in this subsection already exist in the literature, but they were only applied to systems with relative degree one. The considered WLLS has relative degree two. Therefore, the novelty is the application of the controller to systems with relative degree two. Only a few papers focus the adaptive λ-tracking problem for system with relative degree two, but the feedback law here is simpler than the introduced ones in [3], [8], [4]. These controllers achieve λ-tracking (for the proofs see [1]).

SIMULATIONS

We apply the presented simple adaptive λ-tracking control strategies to our WLLS in order to track a given reference signal: a kinematic gait developed in [7]. We try to track the "fast gait" in [7] in our dynamical theory, it is for $t\in[0,1]$:

$$t\mapsto y_{ref}(t)=\begin{pmatrix} \begin{cases} l_0[1-\varepsilon(-1+\cos(3\pi t))] & ,\, t\in[0,2/3) \\ l_0 & ,\, t\in[2/3,1) \end{cases} \\ \begin{cases} l_0[1-\varepsilon(1-\cos(3\pi t))] & ,\, t\in[0,1/3) \\ l_0[1-2\varepsilon] & ,\, t\in[1/3,2/3) \\ l_0[1-\varepsilon(1+\cos(3\pi t))] & ,\, t\in[2/3,1) \end{cases} \end{pmatrix}, \qquad (15)$$

where l_0 is the original length (dimensionless chosen as 2 units) and $2\varepsilon=0.3$ is the elongation. This gait is periodically repeated. Mind that one point mass is resting (active spike) at any time. In order to detect differences we present the simulation results with the λ-trackers (6) and (5), respectively, side by side.

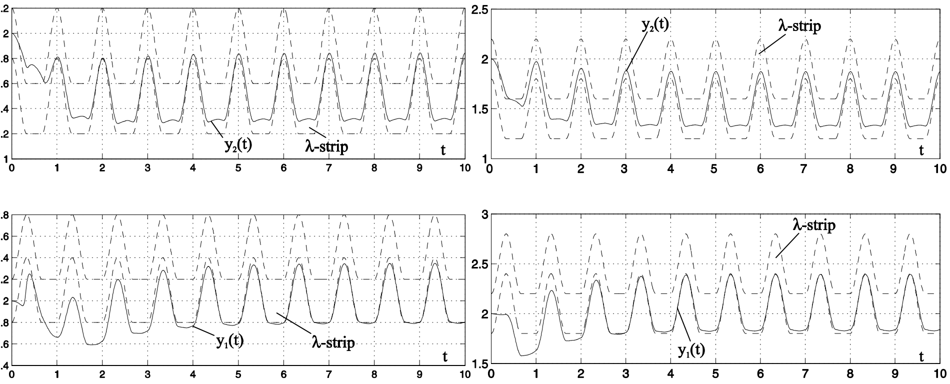

Fig. 3. Outputs and λ-strips – left: for (6), right: for (5)

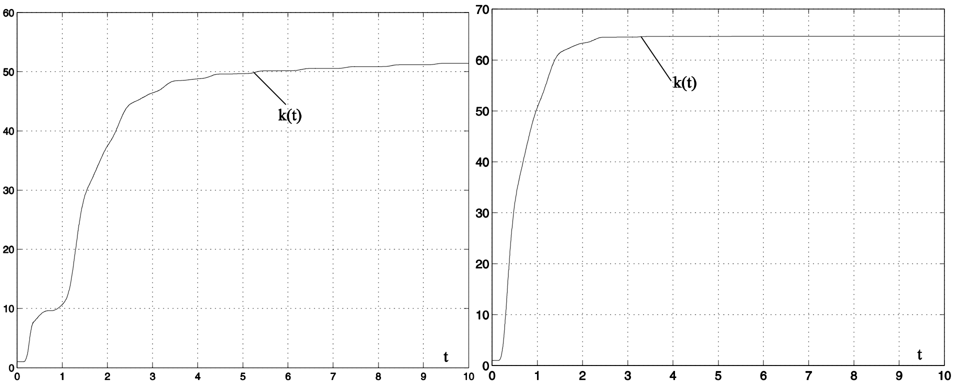

Fig. 4. The gain parameters - left: for (6), right: for (5)

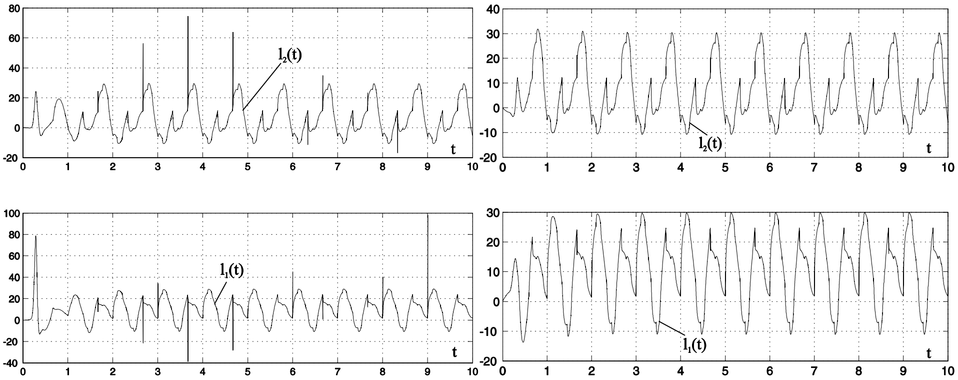

Fig. 5. The control inputs - left: for (6), right: for (5)

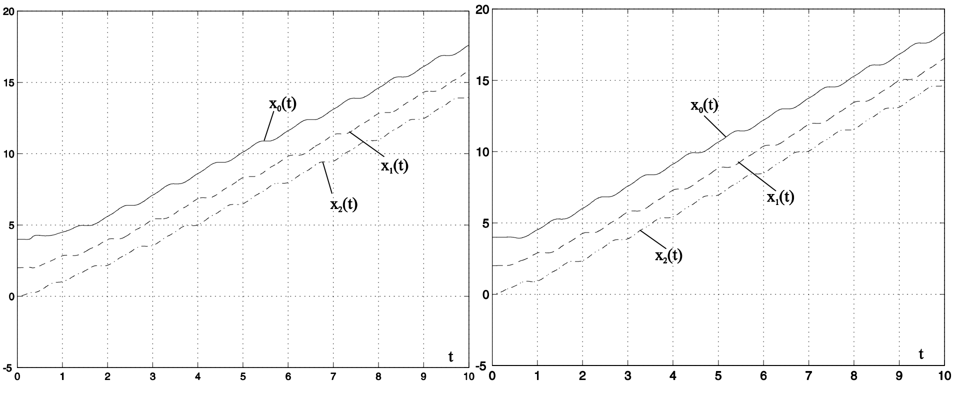

Fig. 6. The motions of the worm - left: with (6), right: with (5)

Fig. 3 shows the outputs of the systems and the according λ-strips. The reference signal is tracked very quickly with controller (5) in comparison to controller (6). In Fig. 3, left, the outputs are not captured yet. The gain parameters, shown in Fig. 4, increase as long as the outputs are outside the λ-strips. Fig. 5 shows the necessary control inputs, and Fig. 6 the corresponding motions of the worm.

It can be seen that controller (5) works more effectively than controller (6) because we feed back more information about the output derivative than (6), which has to estimate the derivative. Hence, in the simulation with controller (6) , the outputs are not captured on the considered time interval and the gain parameter is still increasing. Fig. 4, right, clearly shows the convergence of the gain parameter in the simulation with controller (5).

SUMMARY AND OUTLOOK

The motion of an earthworm was the inspiration for a (technical) solution of an artificial worm. In [7] a theory is developed for the peristaltic motion of such systems, which to a large extent allows to characterize these motions already on a kinematic level. Here, the advantage of adaptive control for the dynamical realization of these motions (tracking of kinematic gaits) is shown. The numerical simulations demonstrate and illustrate that the adaptive controllers work successfully and effectively. We point out, that the adaptive nature of the controllers is expressed by the arbitrary choice of the system parameters. It is obvious that for numerical simulation the system data have to be chosen fixed and known, but the controllers are able to adjust their gain parameter to each set of system data.

References:

[1] Behn, C. (2005). Ein Beitrag zur adaptiven Regelung technischer Systeme nach biologischem Vorbild, Cuvillier, Göttingen

[2] Behn, C. & Zimmermann, K. (2006). Adaptive lambda-tracking for locomotion systems, Robotics and Autonomous Systems, 54, pp. 529-545

[3] Dragan, V. & Halanay, A. (1999). *Stabilization of Linear Systems*, Birkhäuser, Boston

[4] Miller, D.E. & Davison, E.J. (1991). An adaptive controller which provides an arbitrary good transient and steady-state response, *IEEE Transaction on Automatic Control*, 36, pp. 68-81

[5] Ostrowski, J.P.; Burdick, J.W., Lewis, A.D. & Murray, R.M. (1995). The mechanics of undulatory locomotion: the mixed kinematic and dynamic case, *Proc. of IEEE Intern. Conf. on Robotics and Automation*, pp. 1945-1951, Nagoya, May, 1995, Japan

[6] Steigenberger, J. (1999). On a class of biomorphic motion systems, *Preprint No. M12/99*, Faculty of Mathematics and Natural Sciences, TU Ilmenau, Germany

[7] Steigenberger, J. (2004). Modelling artificial worms, *Preprint No. M02/04*, Faculty of Mathematics and Natural Sciences, TU Ilmenau, Germany

[8] Ye, X. (1999). Universal lambda-tracking for nonlinearly-perturbed systems without restrictions pn the relative degree, *Automatica*, 35, pp. 109-119

[9] Zimmermann, K.; Steigenberger, J. & Zeidis, I. (2003). On artificial worms as a chain of mass points, *Proceedings of 6th International Conference on Climbing and Walking Robots (CLAWAR)*, pp. 11-18, Catania, September, 2003, Italy

Authors:

Dr.-Ing. Dipl.-Math. Carsten Behn, Univ.-Prof. Dr.-Ing. habil. Klaus Zimmermann
TU Ilmenau, Faculty of Mechanical Engineering, Max-Planck-Ring 12 (Building F), 98693, Ilmenau
Phone: +49 3677 691813 / Fax: +49 3677 691823
E-mail: carsten.behn@tu-ilmenau.de