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BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS  
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Booklet of PhD Theses

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DYNAMICS OF ROBOTIC AND HUMAN  
POSITIONING AND CONTACT PROCESSES

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## **Introduction**

The current Ph.D. thesis deals with the dynamics of robotic and human positioning and contact processes, and the kinematics of human functional movements. First, the simplified mechanical model of a PI controlled hydraulic cylinder is analysed; analytical, numerical and experimental results are also presented. Subsequently, a novel model of the approach-and-touch process is discussed, in case of stiff targets with low damping and/or inaccurate position feedback. Finally, the dynamic time warping algorithm is examined. The method was implemented in the analysis of human functional movements in activities of daily living. The performance of a post-stroke patient can be quantified by comparing his/her functional movements to the reference ones.

Intense studying of human functional movements may not only be important in post-stroke rehabilitation, but deeper understanding of human motion control can also lead us to enhanced control strategies for robotic approach-and-touch processes, since all the selected ADLs include some kind of interaction with ADL objects that need to be localized, approached, gripped and then somehow manipulated. This procedure requires both position and force control, moreover, in most of the cases a compound of those, and besides the duality of control, mathematical description of approaching and touching an object results a piece-wise discontinuous system.

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## Nonsmooth dynamics of a hydraulic positioning system

Hydraulic systems are widely used in heavy-duty industrial applications, where the exertion of high forces with large stiffness are needed in a robust way. Although there is a considerable effort on developing advanced control strategies, PID control still remains the most popular choice. In the mean time, it is well-known that strong nonlinearities are present in these systems, such as the pressure vs. flow rate relationship, the dead zone of the control valves, the dry friction and the impact dynamics. The sampling time of the closed-loop digital control introduces additional complexity.

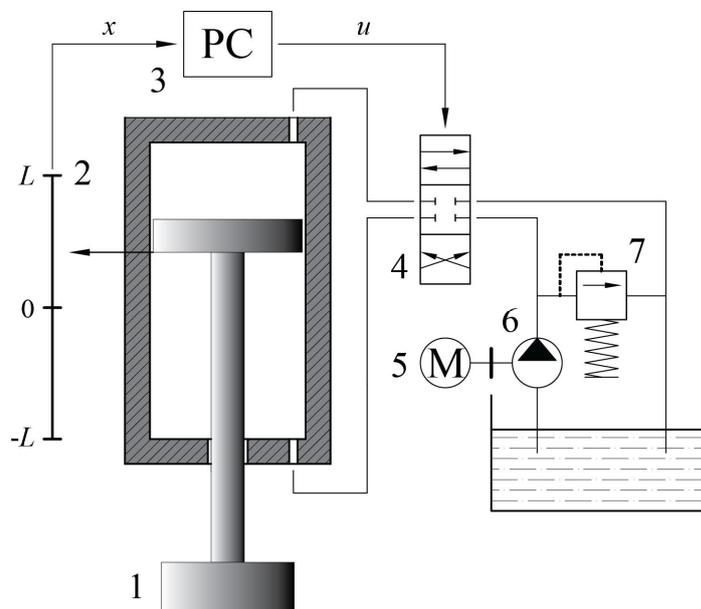


Figure 1. The hydraulic positioning system. 1: hydraulic cylinder, 2: position transducer, 3: PC on which the PI controller is implemented, 4: proportional directional valve, 5: electromotor, 6: gear pump, 7: pressure limiting valve.

## Optimizing contact transitions

It is a common task in robotics and computer-integrated manufacturing to approach and get in touch with an object, and then apply a desired contact force on the surface of the object. A typical problem is polishing, for example; there has been a considerable effort on developing advanced control strategies for this

field of application. This procedure requires both position and force control, moreover, in most of the cases a compound of those, and besides the duality of control, mathematical description of approaching and touching an object results a piecewise discontinuous. In this section, the simple mechanical model of an approach-and-touch control procedure is discussed. The aim is to find an appropriate control strategy to approach the target surface, handle the contact transitions and apply the desired force on the contact surface.

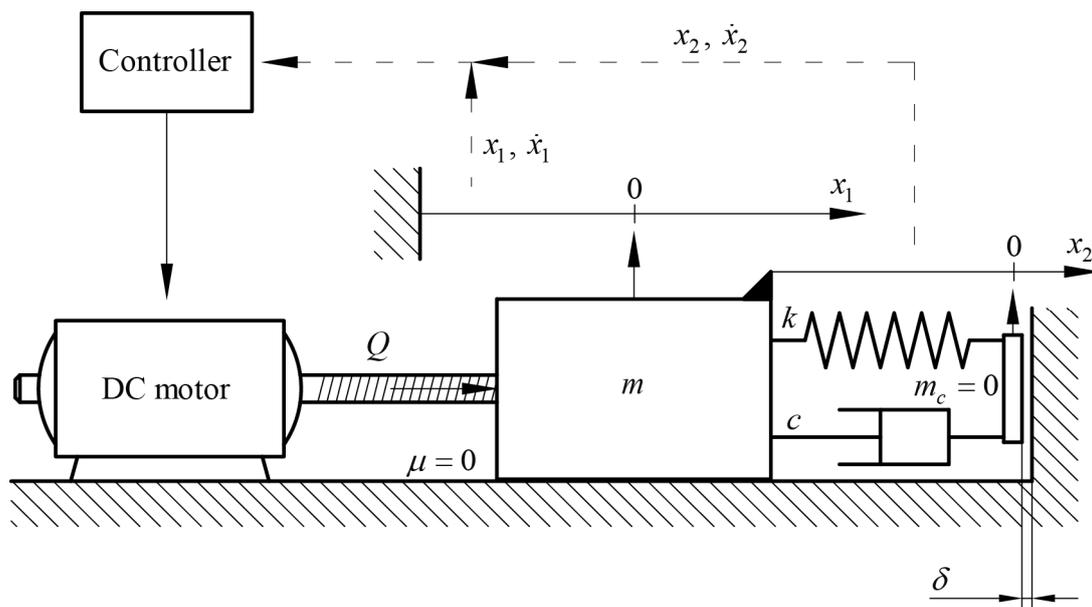


Figure 1. Mechanical model of the approach-and-touch task.

## Quantification of human functional movements

This part of the doctoral thesis presents the application of the dynamic time warping algorithm in the analysis of human functional movements in activities of daily living (ADLs). Dynamic time warping was originally developed for automatic speech recognition, though the method has been adopted by several fields of biomechanics. The aim is to evaluate the measured human functional movements also called the ADLs, i.e. to qualify those with a single scalar. The difference of the measured and the reference ADL data sets can be used to evaluate the patients' performance.

## Theses

### Thesis 1

The simplified mechanical model of a PI controlled hydraulic cylinder was established for the case of stiff gear pumps. The linear mathematical model of the positioning system was constructed, and the stability boundaries were computed and represented in the (P,I) parameter plane. The analytical stability boundaries for the control system were confirmed quantitatively by the measurement results carried out on a test rig. Based on the slight quantitative deviation of the stability boundaries between the theoretical and experimental results, the mathematical model was extended with nonsmooth valve characteristics.

Related publications: [1] and [5].

### Thesis 2

The presence of non-symmetry in the hydraulic positioning system was identified and confirmed by laboratory experiments; the phenomenon is caused by the difference in the two piston face areas. The effects of the non-symmetry on the stability were explored numerically and it was shown that the nonsmooth dynamical system undergoes a special kind of bifurcation that cannot be coped with using linearization techniques. The stability boundaries of the piecewise linear system were determined analytically. It was proved that nonsmooth bifurcations of period-3 orbits occur along the specific stability boundaries

$$\det(\Phi_1\Phi_1\Phi_2 - \mathbf{I}) = 0 \quad \text{and} \quad \det(\Phi_1\Phi_2\Phi_2 - \mathbf{I}) = 0,$$

where  $\Phi_1$  and  $\Phi_2$  are the linear maps for the two states of the piecewise linear system and  $\mathbf{I}$  is the identity matrix. Due to the combinatorial explosion at period- $n$  orbits as  $n$  tends to infinity, infinite number of such stability boundary curves born in case of asymmetry, as verified also by the numerical results.

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Related publications: [2] and [6].

### **Thesis 3**

The influence of control valve dead zone on the global dynamics of a hydraulic positioning system was explored. The positioning system with backlash and time delay can be described by a piecewise linear dynamical model with 9 different linear dynamics. It was proven that the stability of the linear system without backlash is inherited by an invariant set in the phase space of the nonsmooth system, which also includes the original fixed point; both periodic and dense orbits are present in the nonsmooth system when the control parameters are tuned onto the stability boundaries of the backlash-free system. Moreover, it was shown that as the linear coefficient matrices of the piecewise linear system are independent of the dead zone width, so does the stability of the periodic or dense orbits. In other words, the stability boundary of the linear system provides a practical stability margin for the system with backlash, too.

Related publication: [1].

### **Thesis 4**

The approach-and-touch process was modelled in case of stiff targets with low damping and/or inaccurate position feedback in cases when the approach phase takes the relevant part of the transition time. A time-optimal open-loop control strategy was designed with respect to the length of the approach phase, and the corresponding bang-bang-like computed-torque was calculated for the contact phase. It was proved that the maximum velocity of approach can be achieved in case of a four-step scenario. This scenario includes a grazing before the desired contact force is reached, which may lead to undesired multiple impacts in case of parameter uncertainties, signal noise and sampling effects in the digital realization. It was shown that the impacts can be avoided if a simple closed-loop dif-

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ferential control is added to the three-step open-loop control strategy. Simulation results indicated the robustness of the applied method.

Related publications: [3] and [8].

### **Thesis 5**

The Dynamic Time Warping (DTW) algorithm was implemented in the analysis of human functional movements in activities of daily living (ADLs). Based on the experiences in a post-stroke rehabilitation project, the demand raised for quantifying the ADL performances of hemiparetic subjects with a single scalar in order to be able to track their progress during physiotherapy.

A comparison method was developed based on DTW; by tuning the weight parameters of the proposed algorithm, two clusters had been evolved in the scatter plots of control and hemiparetic ADL performances. One contains the performances regarding both arms of control subjects and the nonparetic arm of hemiparetic subjects, and the other cluster is built up by the paretic arms of the stroke affected subjects. It was demonstrated that the performance of a post-stroke patient can be quantified as its distance from the cluster consisting of the reference ADL performances, i.e. the rehabilitation progress can be tracked by an objective, sensory based scale, which is lacking the possible errors related to human motion cognition.

Related publications: [4], [7] and [9].

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## Publications

### Journal articles

- [1] Magyar B, Hős C, Stépán G, Influence of control valve delay and dead zone on the stability of a simple hydraulic positioning system, *Mathematical Problems in Engineering*, Volume 2010, Article ID: 349489, 15 pages, doi: 10.1155/2010/349489. (IF = 1.082, independent citations: 7)
- [2] Magyar B, Stépán G, Hidraulikus pozicionálás szakaszosan lineáris dinamikája, *GÉP folyóirat*, in press, 2015.
- [3] Magyar B, Stépán G, Time-optimal computed-torque control in contact transitions, *Periodica Polytechnica - Mechanical Engineering* 56:(1) pp. 43-47. (2012).
- [4] Magyar B, Stépán G, Chen I-M, Dynamic time warping analysis in post-stroke rehabilitation, *Biomechanica Hungarica*, in press, 2015, 7(2):47–54.

### Conference articles

- [5] Magyar B, Hős C, Stépán G, Stability Measurement of a digitally controlled hydraulic positioning system, *Proceedings of the Seventh Conference on Mechanical Engineering*, 2010, Budapest, Hungary.
  - [6] Magyar B, Stépán G, Exploring global stability in a nonsmooth dynamical model of hydraulic cylinders, *ESMC-2012 - 8th European Solid Mechanics Conference*. pp. 101-102, Graz, Ausztria.
  - [7] Magyar B, Stépán G, Jurák M, Gelányi L, Fazekas G, Causo A, Chen I-M, Application of dynamic time warping in the analysis of human functional movements, *The 4th IEEE Conference on Cognitive Infocommunications (CogInfoCom'13): Chapters of the Future Internet Science and Engineering*, pp. 883–884, Budapest, Hungary.
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**Conferences**

- [8] Magyar B, Stépán G, Szabályozási stratégiák érintési feladatokhoz, *In Attila B, Edgár B and Sándor S, editors, XI. Magyar Mechanikai Konferencia*, p 74, Miskolc Egyetemváros, Hungary.
- [9] Magyar B, Stépán G, Jurák M, Gelányi L, Fazekas G, Causo A, Chen I-M, Dinamikus idővetemítésen alapuló funkcionális mozgáselemző szoftver fejlesztése, *Orvosi Rehabilitáció és Fizikális Medicina Magyarországi Társasága XXXII. Vándorgyűlése*, Miskolc, Hungary, 2013.
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