ROBUST-ADAPTIVE CONTROL OF NONLINEAR SINGLE-VARIABLE MECHATRONIC SYSTEMS AND ROBOTS

(Nemlineáris egyváltozós mechatronikai rendszerek és robotok robusztus-adaptív irányítása)

Summary of PhD thesis by

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1 Introduction

Many industrial applications require precise positioning of a mechanical system, namely moving an object in a given position in space with a given orientation. Some common applications are material manipulation with industrial robots or cranes, positioning in Hard Disk Drives or optical drives. Other applications require a controlled motion in space along a predefined path, for example welding, spray painting with robots, path tracking of unmanned vehicles or guided missiles (trajectory tracking). These tasks are commonly solved with feedback control: the position and the velocity of the mechanical system is measured, and depending on the desired position and the measurements a control algorithm calculates the command signal for electric motors or other type of actuators which drive the mechanical system to obtain zero or acceptably small difference between the real and desired position.

In order to obtain precise positioning, the model of the controlled mechanical system should also be taken into account in the control algorithm. Generally, the mathematical model of the mechanical systems are inherently nonlinear. If we have rotational motion in the system, the nonlinearities could be given by the centrifugal or Coriolis forces. These types of nonlinearities are continuous. There are also other types of discontinuous nonlinearities such as the friction that should be taken into consideration in the modelling [13]. In the case of the friction, the parameters can be measured with difficulties moreover they are time varying. Due to the friction phenomena even in the case of such Single Input Single Output (SISO) mechanical systems [14], which otherwise could be modelled by linear differential equations, the nonlinearity appears and greatly influences the motion [15, 16].

In many practical applications the standard linear Proportional Integral Derivative (PID) type or linear cascade controllers are used for position control. However, when the desired precision is high, or for the path tracking type control
tasks, these controllers cannot assure satisfactory performances. The main reason for this is, that generally the linear controllers cannot compensate efficiently the nonlinearities. This is why the nonlinear control technique became popular to solve tracking and high precision positioning problems.

The differential geometric methods have rendered the design of controllers for a class of nonlinear systems somewhat systematic. This method is based on coordinate transformations by which a class of nonlinear systems can be transformed into linear systems through feedback (feedback linearization) [17]. For the obtained linear system linear controllers may be designed using classical linear control techniques. In the robot control systems the special proprieties of the robot dynamics can be explored and the feedback linearization problem can be solved easier, than for a general nonlinear system. However, these methods cannot be applied for discontinuous nonlinearities, when the nonlinear part in the model is not differentiable.

In many cases the parameters of the systems are only known with a given precision (such as inertias) or some parameters are unknown or time varying (such as friction parameters, mass of the load). Moreover, in many control applications the used models for control are approximate models, they do not describe some phenomena such as the flexibility of a robotic link. At the other hand the control system is also influenced by external disturbances and measurement errors. These uncertainties highly influence the quality of the control.

To handle modelling uncertainties and external disturbances, robust control methods were introduced such as the well known variable structure (sliding mode) control [18], which can be applied effectively for the control of nonlinear systems. This control method has shown to achieve robust performance by effectively accounting for parameter uncertainties and unmodelled dynamics.

In some control tasks, the systems to be controlled have large parameter un-
certainties at the beginning of the control operation, which highly influence the quality of the control. To handle these uncertainties, adaptive control methods can be applied [19], which gradually reduce the parameter uncertainties during the control, hence achieves better tracking and transient performances [20, 21]. If we have to deal with high model uncertainties, the nonlinear part of the model may be approximated with neural or neuro-fuzzy system [22, 23], whose parameters may also be tuned on-line.

The classical adaptive control algorithms cannot deal efficiently with disturbances and unmodelled dynamics, which can cause undesired transient behavior or even instability in the adaptive control system. To handle this problem, robust-adaptive control methods can be applied [24], which modify the control algorithm and the adaptation algorithm in order to deal with uncertainties and disturbances, and at the same time to achieve the desired precision and transient performances. These controllers generally combine the sliding and adaptive control techniques with robustified adaptation algorithms and they assure stability and desired performances in the control system in the presence of uncertainties.

2 Goal of the research work

The main goal of the research is the development of control algorithms for high precision position tracking tasks in the presence of large modelling uncertainties and external disturbances.

Both theoretical (guaranteed stability, guaranteed tracking precision, boundedness of all the signals in the control loop) and practical (applicability, implementability) aspects of the developed algorithms will be discussed in detail. During the research work it was observed, that one of the major source of uncertainty in mechanical control systems is caused by friction. This is why
the discussion of friction modelling and compensation problems represents the dominant part of the work.

Within this framework three groups of problems were addressed:

- Improved adaptive control algorithms, which guarantee the boundedness of the control signal and the stability of the control loop in the presence of large modelling uncertainties or when there are large changes in system parameters.

- Development of a friction modelling, identification and compensation method for positioning systems, which can easily be implemented in simple industrial controller architectures, such as microcontrollers or embedded systems. At the other hand the compensation algorithm should guarantee a prescribed tracking accuracy in the presence of dominant frictional effects.

- Extension of the developed friction compensation methods for robot control systems, combined with on-line payload estimation algorithms.

3 Research methodology

In order to achieve the proposed goals both theoretical and practical methods have to be applied during the research.

For stability analysis, mainly Lyapunov methods are applied. Similarly, the Barbalat lemma has been applied in many theoretical discussion, to analyse the boundedness and convergence of the signals in adaptive control systems.

To show the applicability and performances of the control algorithms both simulations and experimental measurements are applied.

For the simulations of adaptive control systems the MATLAB/Simulink environment has been used. The adaptive and control algorithms are developed
in *MATLAB* language and introduced in Simulink using *S*-functions.

Some algorithms have been tested on physical systems as well. Two experimental setups were used. In the first thesis group a laboratory ball and beam system has been used, designed by *AMIRA* company for research and education. The mechanical system has been controlled using a *dSPACE* card equipped with Digital Signal Processor (*DSP*). The card can be programmed using *Simulink* blocks. The control algorithm has been implemented in *C* language written *S*-Function.

For the friction measurement and compensation an experimental setup was built during the research work. (see Figure 1) It consists of a permanent magnet *DC* servo motor, which drives a metal disc through a gear-head. Friction is introduced via a metal surface, which is held against the disc. For the implementation of friction identification and compensation algorithms, a control board equipped with a microcontroller was developed. (see Figure 2) The control algorithm is implemented on a *PIC − 18* type microcontroller, which *C* compiler allows floating point representation.
4 Summary of new scientific results

1st Thesis Group - Improved nonlinear robust-adaptive control algorithms

I have developed a new adaptive control algorithm for single input nonlinear systems, which can guarantee the boundedness of the control signal in the critical phases of the adaptation. The algorithm solves the singularity problem, which can often occur in other adaptive control systems at the beginning of the adaptation or at large parameter variations, and can lead to infinitely high (unimplementable) control signal. I have shown that the new adaptive algorithm can be applied for the embedded control of underactuated mechatronic systems with unknown system parameters.

I have elaborated a new supervisor control algorithm for neural-adaptive control of single input nonlinear systems, which takes into consideration the effects of modelling errors in adaptive laws as well. I have shown that the developed supervisor control algorithm guarantees the boundedness of all the signals in the control system.

The publications related to the thesis group are: [1, 2, 3]

1.1. I have developed a new adaptive control algorithm for systems given by the model $y^{(n)} = f(x) + g(x)u$, which modifies the control algorithm during the critical phases of the adaptation by introducing a properly chosen switching function. The algorithm solves the problem which can occur in the classical adaptive control algorithms, that the improper estimation of the nonlinear function $g(x)$ can lead to unimplementable control signals even if the system model satisfies $|g(x)| \geq g_m > 0$. I have formulated the control law as:

$$u = \frac{1}{\hat{g}(x) + \rho(\hat{g}(x))\delta} \left( -\hat{f}(x) + u_{lin} \right)$$
where the value of the switching function $\rho(\hat{g})$ is zero, when $|g(x)| \geq g_m > 0$. I have shown that the developed control algorithm guarantees the boundedness of all the signals in the adaptive control system and can solve the path tracking problem.

1.2. I have introduced a new error metrics for the control of underactuated mechatronic systems, which contains the tracking error and punishes the undesired oscillations. I have shown that the new error metrics can be applied for the control of mechatronic systems, which cannot be controlled with feedback linearization.

The applicability of the control has been proved through experimental measurements on a ball and beam system, where the position of the ball has been measured using an image processing system. (The transients of the ball position and the amplification parameter are shown in Figure 3) The experimental
results have proved, that the proposed control algorithm can solve the high precision control of underactuated mechatronic systems with unknown parameters.

1.3. I have developed a new (indirect) adaptive control algorithm for non-linear systems based on neural models, which compensates the effect of large model uncertainties and approximation errors using a supervisor control algorithm, and takes into consideration the maximal error of the regressors both in the control algorithm and in the adaptation laws as well.

a) I have assumed that the model uncertainties (δ) appear in the following form in the system nonlinearities: \( f = \theta_f^T (\xi_f + \delta) = \theta_f^T \xi_f \delta \). I have proved that if the adaptation law has the form: \( \dot{\hat{\theta}}_f = \Gamma S \xi_f \delta \), then the supervisor control law can guarantee the boundedness of the tracking error.

b) I have shown that the supervisor control algorithm integrated with RBF neural network system model can effectively be applied for the control of mechatronic systems with nonlinear friction.


\textit{I have developed a new friction model for the description of low velocity friction phenomena, which can easily be introduced in adaptive control algorithms. Based on the properties of the friction model, a new measurement and off-line identification algorithm has been elaborated for the estimation of nominal model parameters. The method can separate the frictional effects in the measurement signals forcing the mechatronic system in constant speed regimes. For the on-line compensation of friction force caused by non-nominal, slowly time varying friction effects, I have introduced a new adaptive control algorithm, which can solve the tracking problem of the positioning systems. For the study of complex (Coulomb, Striebeck, viscous, Tustin) friction models, I have developed a}
mechatronic testbed system and a control architecture, which assures the verification of the theoretical results on real physical system.

The publications related to the thesis group are: [4, 5, 6, 7, 8, 9]

2.1. I have introduced a new model for the description of the nonlinear frictional behavior at low velocities, whose general form is: $F_f(v) = \theta^T_f \xi_f(v) + F_D(v)$; $F_D \leq \theta^T_{fD} \xi_{fD}(v)$ integrating the Lu-Gre dynamic and the static Tustin friction models (see Figure 4). The first component of the model describes the static frictional behavior and it can be written in a linearly parameterized form. The second component describes the dynamic frictional behavior whose upper bound can also be written in linearly parameterized form. I have shown that the model has the following properties:

a) The model parameters have physical meaning, there is a connection between the parameters of the introduced model and classical friction models. In the new model the Coulomb, viscous, static friction coefficients and the Striebeck velocity can be separated. It has been shown that the sign of the model parameters and their relative magnitudes can be determined in advance, which can be applied to determine the initial values of the estimated parameters at the beginning of the on-line adaptation.

b) I have shown that based on the introduced model it is possible to predict whether there is a limit cycle in low velocity regime caused by friction
in the mechatronic system controlled by classical PD regulator. The limit cycle appears due to the instability phenomenon that occurs in the low velocity regime, under Striebeck velocities. The instability can appear because of wrong controller parameter settings, and it can be predicted based on the introduced model. I have developed a relation between the slope of the Striebeck curve at low velocities ($b_1+$), the mass of the load ($m$) and the amplification of the derivative term ($K_D$), to avoid the limit cycle at low velocities: $K_D \geq b_1+/m$.

2.2. I have developed a two step measurement and hybrid identification method to determine the model parameters. In the first step the friction characteristic is determined from the measurement of the friction force in function of velocity, by introducing the positioning system in constant speed regimes. In the second step the model is fitted to the measured characteristic. The hybrid identification method determines the parameters $\theta_f$ using Least Squares (LS) method. To determine the Striebeck velocity ($v_{sw}$) in the regressor vector $\xi_f(v)$, I have introduced an analytical relation. The other parameter in the regressor vector ($\beta$), which appears in the exponent, is determined using Genetic Algorithm (GA).

2.3. I have developed an adaptive tracking control algorithm for the compensation of unknown frictional and inertial parameters for positioning systems with unknown load.

a) Based on the introduced friction model, I have developed an adaptive control algorithm for on-line tuning of the linear frictional ($\theta_f$) parameters, the inertial parameter, the nonlinear $\beta$ and $v_{sw}$ frictional parameters of the regressor vector $\xi_f(v)$ and the $\theta_fD$ parameters describing the dynamic frictional behavior. I have proved that the algorithm guarantees the stability of the closed loop system and the convergence of the tracking error metrics $S(t) = e_v(t) + \lambda e_x(t)$ (where $e_x(t)$ is the position error and $e_v(t)$ is the velocity error respectively) into a predefined boundary layer $\Phi > 0$. ($|S(t)| \leq \Phi$, if $t \to \infty$)
b) I have developed a mechatronic testbed system to analyse complex frictional behaviors, which contains a Direct Current (DC) servo motor, a gear-head and a metal disc as external load. The varying friction force is introduced in the system through an external metal surface in contact with the disc. The adaptive algorithm is implemented on an embedded commercial industrial microcontroller. The experimental results show that the developed robust-adaptive control algorithm can be implemented real time even on embedded industrial controllers with low computational capability. (The convergence of the tracking error metrics and the frictional parameters are shown on Figure 5 and Figure 6 respectively.)
3rd Thesis Group - Development of robot control algorithms using friction compensation and payload estimation in robotic systems

I have developed a new robust-adaptive control algorithm for robotic systems in which the inertial parameters (mass, inertia matrix, center of gravity) are known only with low precision, the point-like mass of the payload is totally unknown and static and dynamic frictional forces act separately on each joint independent on each other.

The publications related to the thesis group are: [10, 11, 12]

3.1. I have shown that the dynamic model of a robot can be written in such a form in which the parameters of the robot are separated from the payload mass and the frictional forces and torques:

\[
(H_R(q) + mH_L(q))\ddot{q} + (C_R(q, \dot{q}) + mC_L(q, \dot{q}))\dot{q} + (D_R(q) + mD_L(q)) + F_f(\dot{q}) = \tau
\]

where the matrices $H_R$, $C_R$, $D_R$ do not depend on the payload mass ($m$), and the matrices $H_L$, $C_L$, $D_L$ do not depend on the inertial parameters of the robot.

a) I have developed a new control algorithm, which integrates the variable
structure (sliding) control of the robot with the adaptive compensation of static friction forces and payload mass estimation. The algorithm assumes that the inertial parameters of the robot are only known with a given estimation bound. I have proved that the developed algorithm guarantees the convergence of the tracking error metrics of each joint variable into a predefined boundary layer.

b) I have shown that inside the boundary layer the precision of the trajectory tracking depends only on the order of the uncertainties of the robot inertia parameters and does not depend on the payload mass.

(For a three Degrees Of Freedom cylindrical robot the convergence of the tracking error metrics of the joint variables and the estimated payload mass are shown in Figure 7 and Figure 8 respectively.)

3.2. I have shown that based on the friction model introduced in the previous thesis group the robot control algorithm can be extended with the compensation of nonlinear dynamic frictional effects. I have given the Lyapunov function needed for stability consideration, based on which the stability of the adaptive control system follows from previous theorems.

5 Applications

Nowadays in many industrial applications there is a great demand for control algorithms, which can guarantee high trajectory tracking accuracy. The control algorithms presented in this dissertation can be applied for high precision tracking control of industrial positioning systems and robotic systems in the presence of large model uncertainties and dominant frictional effects.

The applicability and performances of the developed robust adaptive control algorithms have been tested within real-time experiments on a ball and beam system and on a mechatronic experimental testbed system.

The experimental measurements and results show that the developed friction
measurement, identification and compensation guarantee high tracking accuracy and at the same time can be implemented on low cost industrial control architectures. The calculation complexity of the algorithms allows 1 ms sampling period on floating point DSP-s and 5 ms sampling period on fixed point controllers. The control algorithms have been implemented in C language and they can easily be introduced in the embedded control systems of industrial positioning systems.

The control algorithm developed for the ball and beam system can be extended for the control of other underactuated mechatronic systems, such as industrial cranes. The developed friction compensation and payload estimation algorithm can be implemented real time for 6 DOF or redundant robots under QNX operating system.

Some of the research results presented in this dissertation has been used in the education as well in Sapientia Hungarian University of Transylvania.

The research results have become known in the scientific society as conference papers and journal articles. The results have been built into the research project the Hungarian National Research Program OTKA T 042634.

**Publications related to the thesis:**


Other references:


