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PhD Thesis
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Further development and novel applications of the Robust Fixed Point Transformation-based adaptive control

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1 Introduction

The classical adaptive control approaches normally use Lyapunov's 2^{nd} or "direct" method that originally was developed for the investigation of the stability of motion of nonlinear systems in the last decade of the 19^{th} century [Lyapunov, 1892]. In the sixties of the past century his work was translated to English [Lyapunov, 1966] and became the mathematical basis in nonlinear adaptive control design. *Its great advantage is that even in the lack of the existence of closed analytical solutions of the equations of motion various stability definitions can be proved for the controlled motion without knowing its other details.* The classic examples as the *Adaptive Inverse Dynamics Controller (AIDC)*, the *Adaptive Slotine-Li Controller (ASLC)* [Slotine and Li, 1991, Isermann et al., 1992] as well as the *Model Reference Adaptive Controllers (MRAC)* (e.g. [Nguyen et al., 1993, Kamnik et al., 1998, Somló et al., 2002]) were designed by the use of various Lyapunov functions.

In spite of its great advantages this design technology has some drawbacks. At first it is a "complicated" method often burdened by mathematical difficulties. It is easy to see that these mathematical difficulties mainly originate from affording certain "unnecessary luxuries" as follows: the method often guarantees *global stability* that is practically too much: in the practice both the unknown external disturbances and the model parameter uncertainties are *bounded* therefore it is not compulsory to guarantee stability for arbitrarily big model errors, disturbances, and initial states e.g. [Kovács, 2013]; the majority of the so designed controllers does not sharply distinguish between the physical role of the *kinematic* and the *dynamic* details: sometimes force terms are directly fed back without using the dynamic model of the system that results in complicated proofs. Furthermore, the method tries to satisfy *satisfactory conditions* instead *necessary* ones that practically also is "too much"; the solutions normally contain a great number of more or less arbitrary parameters; their optimal setting may need the application of complicated evolutionary technologies (e.g. [Sekaj and Veselý, 2005, Chen and Chang, 2009]).

I also observed that the "traditional" approach in the field of *Model Predictive Control – (MPC)* (e.g. [Grancharova and Johansen, 2012]) also suffered from typical *formal complications*. Such controllers normally are placed into the formal structure of the *"Optimal Controllers"* in which combined cost functions represent the often contradictory requirements that are minimized under the "constraints" defined by the dynamical properties of the systems under control. The classical LQR controller [Anderson and Moore, 1989] is a particular case in which the dynamic model is of LTI type and the cost functions have quadratic structure: in this case it is very easy to design a *Receding Horizon Controller* (e.g. [Jadbabaie et al., 1999]) in which the effects of modeling errors and model-incompleteness can be compensated by frequent redesigning of the time-horizon. In more genera cases the development of this approach is hampered by the complexities in the cost functions and the dynamic models.

In order to avoid the mathematical complications related to the Lyapunov function-based design techniques, as alternative approach, iterative solutions were introduced in adaptive control of robots and other nonlinear systems that have to follow in general non-periodic nominal motion. Its most significant main characteristic features are as follows: a) by applying "sterile distinction" between the role of *kinematics* and *dynamics* purely kinematic formulation of the desired tracking error damping was prescribed; b) the necessary control forces (or other control signals in the case of phenomenologically different physical systems) were calculated on the basis of an available approximate and even incomplete dynamic model; c) by observing the actual response of the controlled system and comparing this response with the model-based expectation the input of the approximate model was iteratively deformed to better approximate the kinematically prescribed *"desired response"*; d) the iteration was generated by a fixed point transformation; e) the need for global stability was generally given up.

In [Tar, 2012] and certain related publications transformations based on simple geometric interpretation were introduced and their applicability for various physical systems were clarified. In 2009 one of these transformations, the *"Robust Fixed Point Transformations (RFPT)"* were found to be especially efficient [Tar et al., 2009]. The method contained only a single kinematic and only three adaptive control parameters and found numerous potential applications e.g. adaptive optimal dynamic control for non-holonomic systems [Tar and Rudas, 2009], quasi-stationary control approach in adaptive emission control of freeway traffic [Tar et al., 2012], etc.

2 Goals and Aims

I realized that by the use of the fixed point transformation-based approach the formal difficulties of the traditional adaptive control methods and the MPC controllers can be generally evaded and a new perspective can be opened for the combination of the "optimal" and "adaptive" approaches. On this reason I decided to tackle the main problems related to the fixed point transformation based methods.

The antecedents of my research concentrated on the behavior of the controller only in the convergent regime. Preliminary steps were done by observing and reducing chaotic fluctuations in the case of Single Input – Single output (SISO) systems. Furthermore various parameter tuning procedures were suggested to tune only one of the control parameters in order to keep the system in the convergent regime.

In my research I determined to conduct systematic investigations regarding the behavior of the RFPT-based controller outside the convergent regime in the case of Multiple Input – Multiple Output (MIMO) systems.

I guessed that bounded chaotic oscillations may occur in the RFPT-based adaptive control of MIMO sysems, so my other aim was to present this phenomenon and suggest a method for its reduction.

Another interesting topic was the ambiguity of the generalization of the RFPT transformation from SISO to MIMO systems.

My other aim was the investigation of the transmission between the monotonic convergent, non-monotonic convergent and oscillating regimes in the hope that in this manner a possible tool can be developed for the stabilization of the convergent regime when there is a need for frequent modification/tuning of one of the adaptive parameters.

Another interesting area of research that was not previously systematically investigated is studying the saturation effects in the adaptive control of chemical reactions (e.g. the negative concentrations cannot be physically interpreted and that in the case of a stirring tank reactor it is impossible to decrease the concentration of a component by purely extracting it from the room of the reaction.) My goal was to investigate how the REFPT-based method can deal with such problems.

Finally I planned to demonstrate the applicability of the RFPT-based adaptive control method for new control paradigms.

3 Investigation Methods

In my investigations the application of essentially two different "fundamental methods" were available for me. In the investigation of certain nonlinearities and that of the RFPT transformation studying the form of the equations the classical function analysis yielded a viable method assuming that the physical system models can be approximated as affine functions of the system-responses. This assumption was supported by the models of Classical Mechanical systems, chemical reactions and neuron models.

For other calcuations in the case of nonlinear systems the equations of motion of which normally do not have solutions in closed analytical solutions I applied numerical simulations by the use of the French SCILAB-XCOS softvare. This package has various numerical integrators and "built in" numerical differentiators. I considered these mathematical tools in a critical manner and when it was found to be necessary I developed my own numerical differentiator for problem solution.

The application of numerical techniques and solutions obtained general acceptance in modern science in which the majority of the problems can be solved only by some numerical procedure (e.g. SVD, polytopic decomposition, egeinvalue problems, etc.).

4 New Scientific Results

Thesis 1: Studying and improving the operation of the RFPT-based adaptive controller outside of its convergent regime

I conducted systematic investigations for the behavior of the RFPT-based controller's operation outside of the region of convergence in the case of multiple (MIMO) dimensional systems.

I have used that idea whenever the response function of the controlled SISO system can be approximated by affine expressions, and the initial signal of the iterative control sequence is between the trivial fixed point and the fixed point that is the solution of the control task the controller produces chaotic, bounded fluctuation in the control signal. This fluctuation corresponds to a "bouncing" motion between two repulsive fixed points.

I have observed that the controller's operation in this case is similar to that of a Sliding Mode/Variable Structure controller with great chattering.

I have illustrated the same qualitative behavior in the case of a 2 DoF and a 3 DoF system via simulations. On the basis of these simulation results I have revealed that the consequences of this chattering are not necessarily fatal from the point of view of the control.

I have successfully generalized the chattering reduction technique first announced in [Várkonyi et al., 2012] for SISO systems to MIMO systems. I referred to the so obtained controller as "Bounded RFPT"-based design.

I have shown that if the initial signal is outside of this region the sequence diverges. I have shown it, too, that this case does not have practical significance because it can be avoided easily by properly setting the control parameters.

The publications strictly related to this thesis are: [1], [2].

Thesis 2: Application of the RFPT-based adaptive control for the special nonlinearities and phenomenological limitations in chemical reactions

I systematically studied the typical nonlinearities occurring in chemical systems. I have identified two types of significant classes: a) the nonlinear equations of motion that typically contain the multiplications of various powers of the concentrations, due to the “Mass Action Law”; b) the phenomenological limitations of the control signals, and that of the concentrations.

While the multiplicative nonlinearities has the usual consequences that the time-derivatives of the state variables nonlinearly depend on these variables, the phenomenological limitations have far more drastic aftermaths: by the use of dense reagents at the input side the concentration of the components within a stirred tank reactor can be selectively increased by the controller, but it cannot be selectively decreased: either each ingredient has to be diluted or the input rate has to be truncated at zero. During such periods the concentration of this component cannot be controlled according to the needs of the prescribed control law. The controller has to wait while this concentration decreases by the internal reactions within the tank.

The other limiting factor is that whenever a concentration achieves the value of zero, its time-derivative can be only non-negative. This nonlinearity is similar to the saturation effects.

I have illustrated the above effects in the case of the Brusselator model that was a significant paradigm of the autocatalytic phenomena. I have shown that in the case of a conventional PID-type control based on the reaction equations without applying the necessary phenomenological limitations nice tracking of the prescribed nominal motion is possible. However, in this case the solution partly lays within the physically not interpretable region.

By the use of the same paradigm I have shown that a carefully designed RFPT-based adaptive controller efficiently can solve the same task so that its solution remains always physically interpretable.

To extend the application field of the RFPT-based adaptive control approach I have studied a more precise model of the chemical reactions in which I took it into consideration that the addition of a given reagent dilutes the other ones, i.e. the concentration of the various ingredients cannot completely separately manipulated. (In the mainstream of the literature this effect normally is neglected.) I have called this effect “input coupling” and have shown that the RFPT-based design can be applied to this model in a contradiction-free manner at the cost of increasing the order of the control task. I have run numerical simulations to illustrate this ability of the RFPT-based design.

I have shown via simulations that this RFPT-based solution can be improved by the application of fractional order derivatives that gives the controller certain robustness with respect to the measurement noises and also allows some increase in the cycle time of the control that may have practical significance in the case of slow sensors.

The publications strictly related to this thesis are: [3], [4], [5].

Thesis 3: Improving the parameter tuning possibilities for the RFPT-based design: the discovery and application of the “Precursor Oscillations”

Based on the observations related to the phenomenon of chaos formation of the RFPT-based control I have proven that if the response function of the controlled system can be approximated by an affine expression, by fixing the adaptive control parameters in the RFPT-based scheme, namely K_c and B_c, the following situation can be created: if the parameter A_c is slowly increased from zero, at the beginning the controller works with monotonic convergence in the “iterative learning”. The speed of this convergence increases with increasing A_c till achieving its maximal value. Following that the controller still remains convergent with further increasing A_c but this convergence has non-monotonic, oscillating nature. I called these oscillations “Precursor Oscillations” because further increase in A_c decreases the speed of convergence and finally ends up in the non-convergent regime of bounded chaotic oscillations.

I have designed a model-independent observer to monitor the occurrence of the Precursor Oscillations and have shown that this observer can be efficiently used in the adaptive tuning of the control parameter A_c. In this manner I made a significant step in the direction of widening the applications of the RFPT-based design that originally suffered from the limitations of the bounded region of convergence.

I have illustrated the applicability of the “Precursor Oscillations”-based technique via simulations for an underactuated mechanical system.

I have also shown the occurrence of the Precursor Oscillations in the case of the Bounded RFPT-based design and illustrated its use via simulations for a 1 DoF mechanical system.

The publications strictly related to this thesis are: [6], [7].

Thesis 4: Practical modification of the original RFPT-based design

In the original RFPT-based design the saturated nature of a sigmoid function was of essential significance: it determined the width of the slot within which the response error's details are taken into consideration.

I have shown that this component can be replaced by a truncated linear function that from mathematical point of view is not a sigmoid function (it is not monotone increasing because having constant parts at ± 1), but it is a very good practical approximation that is easy to realize even by analog circuits. Furthermore its slope can easily be tuned.

The applicability of the so modified adaptive controller was shown via simulations for a fully driven and an underactuated 2 DoF mechanical system.

The publications strictly related to this thesis are: [8], [9].

Thesis 5: Combination of the RFPT-based control with the traditional Luenberger Observer

The traditional adaptive control results partly originate from the field of the adaptive control of robots. In this special application area the mechanical state of the controlled system ab ovo is measured by appropriate sensors the use of which do not require the use of “state observers”. State observers normally have to be used when certain state variables cannot be directly measured. In this case some other measurable quantities are available that are in functional relationship with certain components of the state variables. In the realm of the LTI systems for this purpose a “canonical formulation” is available.

In this Thesis I have shown how the RFPT-based adaptive design can be combined with the classical Luenberger observer in the case of a nonlinear system under control. For the illustrative simulations the model of a nonlinear oscillator was used.

The publications strictly related to this thesis are: [10].

Thesis 6: Novel RFPT-based order reduction technique for nonlinear systems

Whenever the system to be controlled consists of a great number of dynamically coupled subsystems the order of the appropriate model and that of the control task is inconveniently high. The drawbacks are the ample dimension of the initial states as well as the sensitivity of the differentiation to the measurement noises. In such cases it is practical to apply reduced order controllers. The traditional antecedents tackle this problem from the theoretical background of the LTI systems.

In this thesis I have shown that for the control of stable systems the RFPT-based adaptive technique allows a far simpler approach to the problem of order reduction in which the consequences of the order reduction are compensated by that of the other modeling errors without the need for the identification of the various effects. The considered simulations were made for a DC motor driven cart.

The publications strictly related to this thesis are: [14], [21].

Thesis 7: Application of the RFPT-based technique for the control of higher order systems

In certain applications that do not need too high order approach, instead of order reduction the application of higher order controller may be advantageous.

In this thesis I have shown that via completing the RFPT-based design with a polynomial higher order differentiator the method can efficiently solve 4th order control tasks. The basic idea of the applied numerical derivator is the application of a scaling for the time-variable to a scale in which the polynomial fitting yield stable result. Following this calculation the result can be scaled back to the real time scale.

The applicability of the method was shown via simulations for a swinging problem and a more or less artificial paradigm just developed for the purposes of this research (mass-points coupled by nonlinear springs).

The publications strictly related to this thesis are: [15], [16].

Thesis 8: Further applications of the RFPT-based adaptive control design

In the current control literature various modern solutions are in use. The aim of this thesis is to reveal novel applications for which alternative solutions were already found in the literature.

The first example was the control of an aeroelastic wing component based on the antecedents in [Baranyi, 2006, Prime et al., 2010]. For this paradigm I have developed a basic RFPT-based method in [11], and an RFPT-based MRAC solution in [11].

The second example was the adaptive dynamic control of a small airplane model that normally serves as a "benchmarking object" in the control literature in [13].

The other application paradigm that extensively was investigated the adaptive dynamic control of a caster supported WMR driven by two actively driven wheels. In this task the underactuation caused by the non-holonomic constraints and the complexity of the dynamic model in the case in which the location of the mass center point is not a priori known mean the main challenges. The publications strictly related to this part of the thesis are: [14], [17], [18], [19], [20], [21], [22].

5 Further Utilization of the Results

Besides the already demonstrated control applications I see a wide area of application in life sciences where normally typical conditions are prevailing. For instance the phenomenon of Type 1 Diabetes Mellitus has various models from the relatively simple "minimal models" (e.g. [Bergman et al., 1979]) to more complicated multiple compartment models (e.g. [Sörensen, 1985], [Friis-Jensen, 2007], [Magni et al., 2007], [Man et al., 2007] etc.) for which various controllers were designed on the "conventional" basis (e.g. [Chee and Fernando, 2007], [Hovorka et al., 2004], [Herrero et al., 2012], etc.). The main problem is the high variance of the parameters regarding the individual patients. The traditional approaches suffer from the need of state-estimation that normally can be done by the use of some Kalman filter that normally assumes some special statistical distribution of the measurement noises and makes the estimation on the basis of a reliable model (e.g. [Kalman, 1960], [Zhang and Zhang, 2006]). In our case both the reliable model and the possibility for measuring the state variables is impossible. Normally only the insulin intake and the glucose concentration can be measured. My simple approach based on affine models without complex state estimation may open new perspective in this field. The same can be stated regarding the control of various neuron models (e.g. [Hodgkin and Huxley, 1952], [Schmid et al., 2004]).

Another wide area of applications may be the ides of cost function-free adaptive optimal controllers. In the case in which we have only one control signal for controlling the state variables of coupled nonlinear dynamic systems each signal may be controlled individually by different relative order order controllers by the use of the RFPT-based technique. If the compromise between the trajectory tracking of the various state variables is solved by time-sharing instead of minimizing some weighted cost function the realms of the adaptive and optimal controllers can be combined without any formal difficulties.

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Summary

In my Thesis I made an attempt to tackle the wide subject area of *adaptive control of nonlinear systems* on a "non-conventional basis" that was recently initiated. I have revealed that the traditional approaches in the fields of "Adaptive Controllers" and "Model Predictive Controllers (MPC)" suffer from practical deficiencies and formal restrictions that make their development individually difficult and also hampers their efficient integration.

In the design of nonlinear adaptive controllers the prevailing methodology is based on the use of Lyapunov functions therefore – while concentrating on the requirement of "global stability" – does not keep in the center of attention the details of the transients of the controlled motion, it is too restrictive because satisfying "satisfactory" conditions instead of the less restrictive "necessary and satisfactory" ones, mixes the kinematic and dynamical aspects, and uses a lot of free parameters that later can be optimally set according to the practical needs. Creation of an appropriate Lyapunov function for a given task is rather an art than a simple algorithm and needs designers of good skills in Mathematics.

The MPC controllers are designed within the framework of the "Optimal Controllers" in which contradictory requirements can be weighted in a cost function that has to be minimized under the constraints determined by the dynamics of the controlled system. In this framework the consequences of he modeling errors can be compensated by frequent redesign of the time horizon in the "Receding Horizon Controllers”. Computationally cheap solutions can be obtained only for very particular system models and cost functions as the classic LQR controller.

My approach at first turns the control problem into a fixed point task the solution of which is found by a simple iteration according to Stefan Banach’s fixed point theorem. This approach concentrates directly on the details of the transients of the controlled motion, contains only a few control parameters, does not “mix” the kinematic and dynamic terms, allows combination with the optimal techniques but suffers from the deficiency of having only a bounded region of convergence.

The antecedents of my research concentrated on the behavior of the controller only in the convergent regime. Preliminary steps were done by observing and reducing chaotic fluctuations in the case of Single Input – Single output (SISO) systems. Furthermore various parameter tuning procedures were suggested to tune only one of the control parameters in order to keep the system in the convergent regime.

In my research I have initiated the systematic investigations of the behavior of the controller outside the convergent regime in the case of Multiple Input – Multiple Output (MIMO) systems. I have pointed out the existence of bounded chaotic oscillations and have shown that these oscillations can be efficiently reduced by the generalization of the method developed for the SISO systems. A have discovered that by the use of appropriate parameter settings one of the parameters can be tuned by monitoring the “precursor oscillations” by the use of model independent observers. I have initiated systematic investigations regarding the special nonlinearities in the chemical reactions that originate from phenomenological restrictions and have shown that this fixed point transformation-based design can work well in such systems. As an application paradigm I studied the Brusselator model of the auto-catalytic phenomena. I initiated systematic research to extend the fixed point transformation based method from SISO to MIMO systems and also suggested the modification of the main component of the original transformation. Finally I have shown various novel application possibilities for the new method as the control of small airplanes, elastic wing components, and permanent magnet driven electric carts with order reduction.

Regarding further research I plan to elaborate various new versions of fixed point transformations and extend their use in cognitive control.

Tartalmi összefoglalás

Értekezésemben kísérletet tettem arra, hogy a *nemlineáris rendszerek adaptív szabályozásának* széles területét egy nemrég kifejlesztett módszer alapján “nem konvencionális” alapokon közelítsem meg. Felismertem, hogy az “adaptív szabályozók” és a “modell prediktív szabályozók (MPC)” gyakorlati szempontú hiányosságoktól és olyan formális kötelmektől szenvednek, melyek fejlődésüket külön-külön is hátráltatják és integrálásukat nehezítik.

A nemlineáris adaptív szabályozók tervezésében az általánosan uralkodó felfogás Lyapunov függvényeket alkalmaz, következésképp a “globális stabilitás” biztosítására koncentrálva szem elől veszti a szabályozott mozgás tranziensének részleteit, matematikailag túlságosan szigorú, mivel a kevésbé restriktív “szükséges és elégséges” feltételek biztosítása helyett a szigorúbb “elégséges feltételeket” igyekszik betartani, visszacsatolásaiban “keveri egymással” a kinematikai és dinamikai szempontokat, számos szabad paramétert épít be a kapott szabályozóba melyeket utólag lehet a gyakorlati igényekhez jobban igazítani. Egy Lyapunov függvény megtalálása inkább “művészet” mint egy szimpla algoritmus és matematikailag igen jól képzett tervezőt igényel.

Az MPC szabályozókat általában az “optimális szabályozók” formai keretében tervezik amelyben gyakran ellentmondásos követelmények vannak összesúlyozva egy költségfüggvényben melyet a szabályozott rendszer dinamikája által megszabott kényszerek mellet próbálnak minimalizálni. E formai keretben a modell-hibák hatását az időhorizont gyakori újratervezésével lehet korrigálni a “hátráló horizontú szabályzókban”. Számítási igény szempontjából “olcsó” megoldások csak speciális dinamikai modell és speciális költségfüggvény esetén nyerhetők mint pl. a klasszikus LQR szabályozó esetében.

Megközelítésemben a szabályozási feladatot fixpont problémává alakítjuk s azt iterációval oldjuk meg Stefan Banach fixpont tétele alapján. E megközelítés eleve a szabályozott mozgás részleteire koncentrál, csak néhány szabályozó paramétert tartalmaz, nem “keveri” egymással a kinematikai és dinamikai részleteket, és kombinálható az optimális szabályozással, viszont hátránya, hogy csak korlátos konvergencia tartományt tud garantálni.

Kutatásom közvetlen előzményei a szabályozó konvergens rezsimben való működésére koncentráltak. Kezdő lépések történtek “egy bemenetű – egy kimenetű (SISO)” rendszerek esetén megjelenő korlátos kaotikus fluktuációk észlelésére és redukálására. Módszerek lettek publikálva az adaptív szabályozó paraméterek egyikének hangolására annak érdekében, hogy a szabályozó a konvergens rezsimben maradjon.

Kutatásaimmal szisztematikus vizsgálatokat kezdeményeztem “több bemenetű – több kimenetű (MIMO)" rendszerek szabályozásában a konvergenciatartományon kívül. Kimutattam a korlátos kaotikus fluktuációk jelenlétét MIMO rendszerek esetében és megmutattam, hogy azok hatékonyan redukálhatók a SISO rendszerekre már kidolgozott technika általánosításával. Felfedeztem, hogy alkalmas paraméter- beállítás mellett az egyik paraméter hangolhatóvá válik az "előfutár oszcillációk" modell-független megfigyelésével. Szisztematikusan vizsgáltam a kémiai reakciókban fenomenológiai okokból megjelenő speciális nemlinearitások hatását, és megmutattam, hogy a fixpont transzformáció alapú megközelítés jól működik ilyen rendszerekben is. Alkalmazási példaként az autokatalitikus folyamatok Brusselator modelljét használtam. Szisztematikusan vizsgáltam, hogyan lehet a fixpont transzformációs módszert SISO rendszerekről MIMO rendszerekre általánosítani és javaslatot tettem a transzformáció "fő alkatrészének" egyszerűsítésére. Végül különböző új alkalmazási lehetőségeket mutattam meg a fixpont transzformációs módszerre: kis repülőgép valamint rugalmas szárny-komponens mozgásának szabályozását, állandó mágneses DC motorral hajtott robotkocsi rendcsökkentett szabályozását.

A kutatások folytatásaként tervezem új típusú fixpont transzformációk bevezetését és azok kognitív szabályozókban való alkalmazásának vizsgálatát.