ÓBUDA UNIVERSITY

Ph.D. Dissertation
–Thesis Book–

A Study on Using Fixed Point Transformation in Adaptive Techniques in Robotics and Nonlinear Control

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Abstract

In this technologically advanced century, adaptive techniques are widely used in control of robots and nonlinear systems. In controlling the unknown dynamical systems, adaptive methods are considered effective and convenient. Such adaptive techniques can help the controllers to design their systems precisely and they excellently have achieved their desired objectives in this field. For the modeling of robots and other mechanical systems, advanced adaptive techniques and control algorithms can be used to find the stable solutions. During the first decade of this century, a lot of working procedures in the field of adaptive techniques were developed to control the nonlinear systems and robots. The advanced features of soft computing methods were helped the researchers in many areas. These methods were suitably used to solve the nonlinear problems while in many cases those solutions need a bunch of difficult mathematical computations. In such cases, the study of those adaptive techniques in robotics and nonlinear control can further help to understand the model convergence and systems stability issues in real applications. In many cases, the applications of traditional approaches cannot guarantee the highly convergent and stability levels. Therefore, my primary aim to expend the novel Fixed–Point Transformation (FPT) method in many aspects adaptively, to check its performance in nonlinear controls and finding suitable ways to apply this method expediently. In the dissertation the said FPT method was used to evade the non–convenient ways and computational burdens. With the possibilities of the combination of the FPT method and the classical Receding Horizon Control (RHC) provided expedient results and the modification of the traditional models for the illness Type 1 Diabetes Mellitus (T1DM) based on the FPT method provided good results. The verification of the analogy between the novel FPT method and the driving of the gradient of the auxiliary function to zero by the conformed simulation results provided me an advantage in case to calculate the solutions of the nonlinear systems. In the case of robots, one of my prime intention was to remove the burden of Jacobian which in some possible cases found convenient results by FPT methods.

I. Introduction

The theory of controlling nonlinear systems extensively was developed and used in the mid of the 20^{th} century and got more popularity with the passage of time. A revolutionary change was seen after the invention of computer, that made this field easier especially when Rudolf Kálmán placed into the center of attention the state–space model formulated in the time domain instead of the frequency picture that was prevailing before the early sixties of the 20th century.

In the most of the application areas within the frames of "Model Predictive Control" (MPC) [Grüne and Pannek, 2011, Grancharova and Johansen, 2012] the controlled system's dynamics (as a rigorous condition) mathematically is expressed as a "constraint" that has to be met while a "cost function" often representing contradictory requirements can be minimized with compromises. Among these compromises the limitation of the control force (caused by either the saturation of the drives or other reasons) can be taken into account. A possibility for tackling this problem is the method of "Dynamic Programming" (DP) that is based on the variation calculus and the resulting Hamilton–Jacobi–Bellman equation [Bellman, 1954, Bellman, 1957].

To evade the huge computational needs of the dynamic programming approach, in tackling the problems in the field of control the so–called nonlinear programming approach can be applied. The heuristic "Receding Horizon Controllers" (RHC) that were introduced for industrial use in the seventies of the past century [Richalet et al., 1978] approximate the (MPC) over a finite time–horizon by the use of an available approximate dynamic model only, and for the compensation of the consequences of the modeling imprecisions and unknown external disturbances, the controlled system's state is directly observed or estimated by the use of observable data in the last point of the horizon that can be used as a starting point of the next one. Normally, the finite horizon is approximated by a discrete time–grid, and nonlinear programming is used for the calculation of the solution in which the solution is computed by the use of Lagrange's "Generalized Reduced Gradient" (GRG) method published in 1811 [Lagrange et al., 1811].

In the case of using general forms for the cost functions and allowing the use of arbitrary nonlinear models no rigorous statements can be done on the nature of the obtained solutions.

In general, "incompressibility" does not promise very nice numerical behavior for the solutions. If in certain direction the cells are shrunk, in other directions they have to be extended to save their volume. This concerns stability issues: it cannot be expected that the solution can be settled in an attractive point of the state space. On this reason in the practice the otherwise quite wide frames of the RHC controllers are applied under strictly "narrow" conditions as follows:

a) Normally the cost functions are quadratic terms constructed of constant symmetric positive definite matrices and the state tracking errors. Consequently, their derivatives in the reduced gradient method will be well behaving linear functions of the tracking errors.

b) Generally similar quadratic terms are in use for the limitation of the control forces that provides similar advantages.

c) In the case of LTI system models the Lagrange multipliers can be constructed as the product of some symmetric matrices and the state variables. The equations of motion for these matrices can be decoupled from that of the state variables, that is a great advantage.

d) The equations of motion obtained for these matrices satisfy some Riccati equation with some "terminal condition". In the 18th century Riccati realized that special first order quadratic differential equations can be solved by obtaining the solution for linear, second order differential equations [Riccati, 1724]. Therefore, under these special conditions certain "general view" of the solution became available. The matrix versions of the Riccati equations obtained wide scale use in control technology (e.g. [Wonham, 1968, Laub, 1979]).

e) Regarding certain constraints, Schur's matrix complement [Haynsworth, 1968] can be applied to transform quadratic constraints into linear ones that can be efficiently tackled by the LMI techniques as it was recommended by Boyd et al. in [Boyd et al., 1994].

It was considered an open question since a few years ago that the combination of the MPC within the frame of "Optimal Controllers" with some adaptive techniques can be possible in the area of control theory.

In the field of control theory to design nonlinear adaptive controllers, generally Lyapunov's well known 2^{nd} or "Direct Method" [Lyapunov, 1892, Lyapunov, 1966] is used. It is widely applicable in recent days, too. But its typically complex design process is considered as burden and difficult, therefore alternative simple methods were adopted.

To get rid of the very complicated Lyapunov function–based adaptive solutions in 2009 an alternative approach "Fixed Point Transformation" (FPT) was proposed [Tar et al., 2009] where, the problem at first was transformed into the fixed point task and then further the idea of iterative solution of the fixed–point of a contractive map was used.

II. Research Aims in the Mirror of the State of the Art

This is the era of modern sciences and technologies. Things and technologies continuously keep changing due to new ideas and up–to–date technological instruments. Such ideas and the advanced technological revolution bring severe changes in several natural systems in the universe. Abundant of systems are working there in the universe, based on nonlinear functional dependencies. Their non–linearity was always considered a great challenging subject for the researchers in view of their stability and efficient control. The control of such systems, by numerous techniques, fall in the area of study named “Control Theory”.

To deal with such systems only a few methods were used before the last decade of the 19th century but later in 1892 Alexander Lyapunov elaborated his way of solution in his doctoral dissertation to deal with the stability of the systems giving his theory with the approach named as “Lyapunov’s Direct or Second Method” to determine the stability of a nonlinear system without solving its equations of motion. It is evident that, a control designer tries to bring about better and efficient methods to maintain the stability of the controlled systems. In the beginning, getting the solutions of the problems, based on non–linearity, were very hard due to the fact that only “manual working system” (consisting of crank driven mechanical calculators, slide-slip, metric paper and the tabulated form of certain special functions) was available, but later the invention of the computers provided an easy way to proceed in this area of study to extend it and widen its view from different aspects. To understand the working process and criteria of the systems, consideration of their modeling and controlling process, measuring or estimating the states of the systems efficiently have become the prime need of the time. For the purpose of controlling the systems and to understand their stability, different varieties of methods and terminologies have been used in different times to enrich the stabilities.

Adaptive control is one of the method where a system uses the techniques and approaches to change itself according to the behavior in new or a varying circumstances. The motivation to consider this area of study was gotten in early fifties of the previous century when an autopilot high performance based aircraft for high altitudes and wide range of speed was designed. After this approach the study area got more attention in all aspects of life. Examples for a quite rich variety of problems in practical life can be mentioned in this context: the *glucose–insulin metabolism* [Sörensen, 1985, Cobelli and Pacini, 1988, Magni et al., 2007], the pharmaco–kinetics of various drugs in anaesthesia [Naşcu et al., 2015], modeling the operation of the neurons and the nervous system [Lapicque, 1907, Dayan and Abbott, 2001] in life sciences, dynamic models of robots [Armstrong et al., 1986, Corke and Armstrong-Helouvry, 1994], chemical processes like crystallization [Moldoványi, 2012], efficient control of freeway traffic [Bellemans et al., 2003, Luspay, 2011] including the limitation of the emission of polluting materials [Csikós, 2015, Csikós et al., 2015], etc. can emphasize its importance and applicability.

The study of adaptive techniques for nonlinear systems has considerable mathematical difficulties. Analysing them theoretically is, in fact, a very complex and hard task. Therefore, the modern techniques and approaches in view of approximations in control design and signal processing include a various class of mathematical tools.

In the last decade of the 20th century the idea of MPC was vastly investigated (e.g. [Clarke et al., 1987a, Clarke et al., 1987b]), and its novel developments (e.g. [Grancharova and Johansen, 2012]) were successfully used in different fields of the life as e.g. in chemistry [Bequette, 1991], life sciences–related problems [Hovorka et al., 2004], economy [Muthukumar et al., 2016], etc. Another use of advanced control solutions is, to get attention in today's medical practice regarding the control of physiological processes [Bronzino and Peterson, 2015]. Many control solutions are under development which can be used for various kinds of control problems. It has been observed that there are many advanced control methods that have been successfully applied for physiological regulation problems, for example control of anaesthesia [Padula et al., 2015], antiangiogenic inhibition of cancer [Drexler et al., 2017], immune response in presence of human immunodeficiency virus [Zurakowski and Teel, 2006] and regulation of blood glucose (BG) level [Colmegna et al., 2018, Eigner et al., 2016] as well.

In the applications, the nonlinear nature of the advanced control techniques has high importance. Besides the non–linearities in the control problems the researchers on the field, are facing many challenges such as model and parameter uncertainties and even time–delay effects, too.

It is well known that in designing the adaptive controllers, based on the nonlinear systems mostly Lyapunov's "direct" or "second method" is applied as a traditional approach [Lyapunov, 1892, Lyapunov, 1966]. Essentially the same approach is extended to tackling time–delay problems by the use of the Lyapunov-Krasowskii functional [Kolmanovskii et al.,]. The complexity of this method diverted the attention of researchers to propose the alternative simple approaches (e.g. [Tar et al., 1995, Tar et al., 2000, Tar et al., 2001, Tar et al., 1999]). According to the basic facts the work of Lyapunov's method can be summarized as follows [Tar et al., 2010]:

a) it can be used to create the satisfactory conditions to guarantee the stability,

b) it does not focus on the tracking error relaxation in the initial phase of the controlled motion, but provides the opportunity to prove the global stability that is very necessary in common cases,

c) in the case of certain adaptive approaches for the identification of the parameters of the model of the controlled system, it provides significant methods,

d) it works with a large number of arbitrary adaptive control parameters because it contains certain components of the particular Lyapunov function in use, and may require further parameter optimization (e.g. [Sekaj and Veselý, 2005]).

It is realized that the mathematical framework of the traditional MPC can hardly be combined with the Lyapunov function–based adaptive control. Certain approaches combining MPC and Lyapunov's stability theorem can be found in the literature (e.g. [Jadbabaie, n 15]).

Concentrating on the primary design intent the "Robust Fixed Point Transformation" (RFPT)–based technique was suggested in which the non–linearly optimized trajectory can be adaptively tracked iteratively by the adaptive controller that converges to the appropriate point, based on Banach's Fixed Point Theorem [Banach, 1922]. Furthermore, the suggested "adaptive, iterative inverse kinematic approach" [Khan et al., 2017a] – based on [Csanádi et al., 2016, Csanádi et al., 2017] – can be convergent and useful even if the Jacobian of the robot arm is only approximately known. The application of an "abstract" rotational transformation in the state space can improve the convergence properties of the iteration without the need for obtaining complete information on the actual (i.e. the "exact") Jacobian. It is just enough to utilize the simple motion steps generated by the iteration that produces a smooth motion.

Similarly, a possible recent improvement of the RHC approach was reported in [Khan et al., 2017b] that corresponds to the adaptive tracking of the optimized trajectory instead of exerting the forces calculated by the optimization algorithm on the basis of an available, approximate dynamic model.

All the above discussed results were introduced in our papers published recently (e.g. [Khan et al., 2018b, Khan et al., 2017b, Khan et al., 2017c, Khan et al., 2018a], [Khan and Tar, 2019a], [Khan and Tar, 2019c], [Khan and Tar, 2019b], and [Khan and Tar, 2020]).

III. Research Methodology

It is obvious that computational mathematical problems and engineering topics need simulation-based studies to understand and further extend the existing solutions. The wide range of practical problems results in differential equations that cannot be solved analytically can be studied via numerical methods using simulations and programming. Such problems can be applied and understood after the validation of the simulation investigations. For this purpose, a lot of mathematical packages can help to find the clear results.

In the period of my study, I used the "JULIA" Programming Language for programming purposes to find the required results of my research. This method provides an easy way, simple coding, understandable declaration of parameters, and fast executing possibilities with obvious figures. Similarly, the simple VISUAL BASIC of MS–EXCEL 2010 was also used that helped to easily compile the results by a very simple programming coding method. In some cases I used MATLAB 2018, too, to obtain results. Though, MATLAB also provides a very simple environment for programming and the coding is also not too complex but it is too heavy to execute the results. MATLAB helped in several cases when few difficulties in running of the JULIA in Windows created problems. In all cases the discussed packages helped in simulations and ensured the precise results.

IV. New Scientific Results and Theses

These sections are consisting of the results and their details descriptions. In the *Thesis Section*, a short overview of the research will be given while in the subsections their details will be explained. The results based on the same idea with different aspects were discussed in the common thesis points while their explanations will be elaborated separately.

IV.1. Improvement of the Classical Receding Horizon Controller and Its Applications

THESIS 1: *I have proposed significant improvement of the traditional Nonlinear Programming–based Receding Horizon Controllers from two points of view: a) instead of the usual quadratic cost functions I suggested nonquadratic ones applying various, qualitatively interpreted format parameters; b) I invented the idea of the adaptive RHC controller by combining its original concept with the Fixed Point Transformation–based adaptive controllers: the trajectory computed by the traditional optimization was adaptively tracked instead using the traditionally estimated control forces. Based on the concept a) a solution was elaborated and simulated to treat patients suffering from Illness Type 1 Diabetes Mellitus (T1DM) to maintain the Blood Glucose (BG) level in the proposed range. The applicability of concept b) was illustrated by simulations for a simple first order paradigm. In both cases the MS EXCEL's embedded Solver solution was used to achieve the targeted results.*

IV.1.1. Detailed explanation of Thesis-1

A. In order to control Type 1 Diabetes Mellitus a special dynamic system model was taken from the literature (the “Minimal Model”) and subsequently it was modified. The essence of the modification was an extension with a sub–model to describe the absorption of the external glucose and insulin intake because during the daily routine these substances are not directly injected to the blood stream, therefore the characteristic of their appearance in blood has elongated dynamics that is better treatable than a “peak kind” ingress. Two different scenarios have been investigated to test my approach. In the first scenario, I applied “soft” disturbance and smaller penalties via the developed cost function in order to make sure that the controller design is possible at all and appropriate control action can be achieved by using the continuous optimization. In the second test scenario I used unfavorable, cyclic disturbance signal with high amplitude to test the “robustness” of the proposed controller. The developed RHC controller was able to handle the load and provided satisfactory control action. Furthermore, in both cases the BG level was kept in the predefined healthy range. In its structure the suggested approach can be further improved by the combination with a Fixed Point Transformation–based adaptive solution.

B. In case of the combination of the RHC and Fixed Point Transformation (FPT) a novel adaptive RHC controller was suggested in which the available approximate dynamical model of the controlled system is used as a constraint for the calculation of the estimated optimized trajectory and the control signals over a finite time–grid in a Nonlinear Programming (NP) approach. In contrast to the traditional RHC that exerts the so estimated control signals and consecutively redesigns the tracking horizon, in my approach the so estimated optimized trajectory is adaptively tracked by a Robust Fixed Point Transformation-based Adaptive controller. The applicability of this approach is demonstrated by a comparative analysis of the operation of the traditional and the novel adaptive RHC controllers for a simple LTI system and strongly non–linear cost functions that exclude the use of the usual LQR approach. These investigations serve as the first step towards developing the adaptive RHC based on NP and

FPT–based design.

Selected Publications Related to the Thesis 1

[T1-1] Hamza Khan, József K. Tar, Imre Rudas, Levente Kovács, and György Eigner: **"Receding Horizon Control of Type 1 Diabetes Mellitus by Using Nonlinear Programming"**, Complexity, Article ID 4670159,https://doi.org/10.1155/2018/4670159",

[T1-2] Hamza Khan, Ágnes Szeghegyi, and József K. Tar: **"Fixed Point Transformation-based Adaptive Optimal Control Using NP"**, In Proc. of the 2017 IEEE 30th Jubilee Neumann Colloquium, November 24-25, 2017, Budapest, Hungary, pp. 35-40, https://DOI: 10.1109/NC.2017.8263279",

IV.2. Adaptive RHC for Special Problem Classes Treatable by the Auxiliary Function Approach

THESIS 2: *I have realized that there is a strict analogy between driving the gradient of the Auxiliary Function to zero in the Receding Horizon Controllers, and the novel, Fixed Point Transformation–based solution of the inverse kinematic task of robots. On this basis I suggested the replacement of the original Reduced Gradient Algorithm with the application of the Fixed Point Transformation–based approach to drive this gradient to zero. In this novel adaptive RHC the FPT–based solution is applied in two different levels: in finding the optimum, and in adaptively tracking the optimized trajectory calculated by the use of the available approximate dynamic model of the controlled system. The method has the "difficulty" that the constraint equations must be analytically expressed before using the approximation over a discrete time–grid, and the Jacobian of the problem has to be computed, too.*

IV.2.1. Detailed explanation of Thesis 2

A: In this part I have introduced a new way based on the idea of driving the Lagrange's Reduced Gradient (LRG) to zero where the numerically much more complex GRG method has been replaced with a simple fixed-point transformation–based adaptive solution. It was also justified that it can easily be implemented in an arbitrary software environment for a wide class of problems in which the gradient of the "auxiliary function" as well as the gradient of this gradient can be determined in closed form formulation. The same type of fixed–point transformation was applied for driving the gradient of the auxiliary function and adaptively tracking of the optimized trajectory by the actual system. The applicability of the method was illustrated by presenting an example of a van der Pol oscillator and nonlinear dynamic paradigm, the Duffing oscillator. The method has the "difficulty" that the constraint equations must be analytically expressed before using the approximation over a discrete time–grid, and the Jacobian of the problem has to be computed, too. The simulations were made by a simple sequential code written in Julia language. It definitely can be stated that the theoretical expectations were verified by the simulations.

B: In the research concerned in this part I have further developed the main idea of the replacement of the original Reduced Gradient Algorithm with FPI procedure that directly drives the gradient of the Auxiliary Function of the optimization problem to zero. To investigate and validate the method a recent solution of the inverse kinematic task evading the calculation of the Jacobian was used. To make this procedure convergent, in the proposed solution for the calculation of the Jacobian only a rough numerical estimation was applied. Furthermore, it was realized that the convergence properties of the new algorithm can be improved by varying its presently established parameters that were experimentally set for the simulations. The method was presented and studied using numerical simulations for a strongly nonlinear, one degree of freedom, 2^{nd} order dynamical system, the van der Pol Oscillator, and 2 DoF 2^{nd} order nonlinear system that consists of two, non–linearly coupled van der Pol oscillators. To guarantee lucid calculations simple functions were introduced that map the active parts of the horizon under consideration to the elements of the gradient of the auxiliary function that are calculated analytically. In general it can be concluded that the calculation or at least some good estimation of the Jacobian can be spared only in very special cases.

Selected Publications Related to the Thesis 2

[T2-1] Hamza Khan, József K. Tar, Imre J. Rudas, and György Eigner: **"Iterative Solution in Adaptive Model Predictive Control by Using Fixed-Point Transformation Method"**, International Journal of Mathematical Models and Methods in Applied Sciences, Vol. 12, pp. 7-15, **2018**

[T2-2] Hamza Khan, József K. Tar, Imre J. Rudas, György Eigner: **"Adaptive Model Predictive Control Based on Fixed Point Iteration"**, WSEAS Transactions on Systems and Control, Vol. 12, pp. 347-354,

[T2-3] H. Khan, J.K. Tar,Károly Sźell: **"On Replacing Lagrange's "Reduced Gradient Algorithm" by Simplified Fixed Point Iteration in Adaptive Model Predictive Control"**, INES 2019 IEEE 23rd International Conference on Intelligent Engineering Systems April 25-27, 2019 Gödöllő, Hungary,

[T2-4] H. Khan, J.K. Tar **"On the Implementation of Fixed Point Iteration-based Adaptive Receding Horizon Control for Multiple Degree of Freedom, Higher Order Dynamical Systems"**, Acta Polytechnica Hungarica, Vol. 16, no. 9, pp. 135-154, DOI. 10.12700/APH.16.9.2019.9.8,

IV.3. FPT–based Adaptive Solution of the Inverse Kinematic Task of Robots

THESIS 3: *I developed a novel method for adaptively solving the differential inverse kinematic task of redundant robot arms in the possession of an approximately known Jacobian. I is a generalization of the method by B. Csanádi that was based on the assumption of exactly known Jacobian. The novelty is the introduction of abstract rotations by the use of which the convergence can be guaranteed without knowing the exact Jacobian. The applicability of the method was investigated via simulatons for an 8 DoF robot arm.*
Furthermore, I made investigations – at least for special cases – aiming at evading the computation of the Jacobian..

IV.3.1. Detailed explanation of Thesis 3

A: On the basis of the quasi–differential approach (in which only the computation of the Jacobian is needed without the calculation of its "generalized inverse") a possible alternative adaptive iterative approach was introduced as "Adaptive Inverse Kinematics" based on the application of the Fixed–Point Transformation (FPT). In this approach no complete information is needed on the Jacobian at a given point. The scientific novelty in this part consists of the fact that the here suggested procedure can be convergent and useful even if the Jacobian of the robot arm is only approximately known. The key factor is a rotational transformation, the application of which can improve the convergence properties of the iteration. It is content with the observable system behavior only along with the realized motion, so it seems to be easily implementable. Its operation is demonstrated for an irregularly extended 6 Degree of Freedom (DoF) PUMA–type robot arm, that has 8 rotary axles. From the simulation–based results it can clearly be stated that the "tendency for divergence" is very small and only very tiny abstract rotations occurred in the simulations. Another outlining possibility seems to be the modification of the fixed–point transformation–based adaptive controllers in order to extend the set of physical systems for which this method can be convergent and practically useful.

B: In the inversion-free quasi–differential solution of the inverse kinematic of a redundant robot the calculation of the Jacobian is required. The computation of Jacobian generally was found to be very laborious, so conducting research to avoid this computational burden was important. I have tried to answer the question whether it is possible to avoid the calculation of the Jacobian in the case of non–redundant robot arms of quadratic Jacobians. As a simple example, a 2 DoF arm was considered via simulations. It was shown that by the use of a simple complementary norm reduction built into the solution this approach was promising. However, for higher degree of freedom systems more investigations seem to be expedient.

Selected Publications Related to the Thesis 3

[T3-1] Hamza Khan, Aurél Galántai and József K. Tar: **"Adaptive Solution of the Inverse Kinematic Task by Fixed-Point Transformation"**,V. In Proc. of the SAMI 2017 IEEE 15th International Symposium on Applied Machine Intelligence and Informatics (SAMI 2017), January 26-28, 2017, Herl'any, Slovakia, pp. 247-252, DOI: 10.1109/SAMI.2017.7880312,

[T3-2] Hamza Khan and József K. Tar: **"Fixed Point Iteration-based Problem Solution without the Calculation of the Jacobian"**,V. In Proc. of the SAMI 2019 IEEE 17th International Symposium on Applied Machine Intelligence and Informatics (SAMI 2019), January 25-27, 2019, Herl'any, Slovakia, pp. 187-192, DOI: 10.1109/SAMI.2019.8782749,

[T3-3] H. Khan, J.K. Tar, **"Fine Tuning of the Fixed Point Iteration-Based Matrix Inversion-Free Adaptive Inverse Kinematics Using Abstract Rotations"**, Journal of Mathematics Punjab University Pakistan,

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My Own Further Related Publications to the Thesis

[T1-3] Hamza Khan, Tamás Faitli, Tamás Szili, and József K. Tar: **“Preliminary Investigation on the Possible Adaptive Control of an Inverted Pendulum-type Electric Cart”**, In Proc. of the IEEE 18th International Symposium on Computational Intelligence and Informatics (CINTI), 21-22 Nov. 2018, Budapest, Hungary, DOI: 10.1109/CINTI.2018.8928229, **2018**

[T1-4] Hamza Khan, and József K. Tar: **“Novel Contradiction Resolution in Fixed Point Transformation-based Adaptive Control”**, In Proc. of the IEEE 18th International Symposium on Computational Intelligence and Informatics (CINTI), 21-22 Nov. 2018, Budapest, Hungary, DOI: 10.1109/CINTI.2018.8928235, **2018**

[A1] H. Khan, J.K. Tar, and Imre J. Rudas **“On The Alternatives of Lyapunov’s Direct Method in Adaptive Control Design”**, Robot Autom Eng J, vol. 3, no. 5, DOI:10.19080/RAEJ.2018.03.555623 **2020**

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