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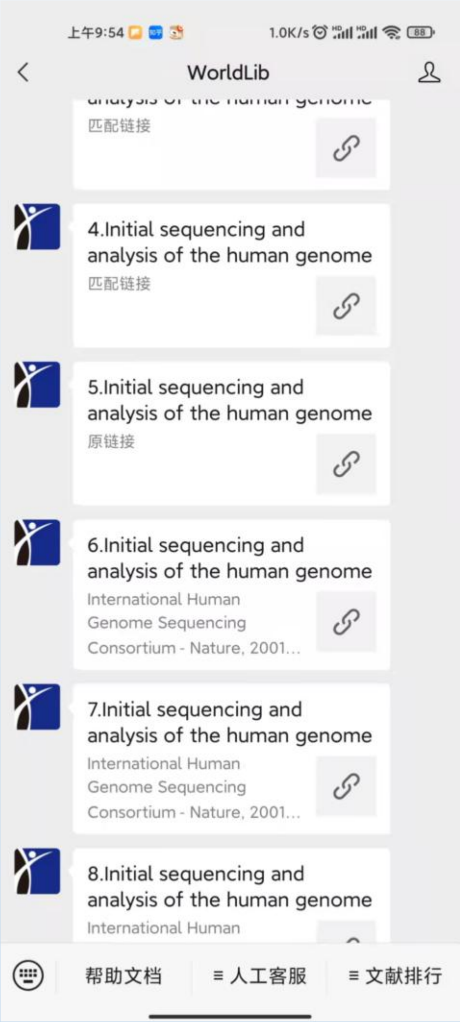

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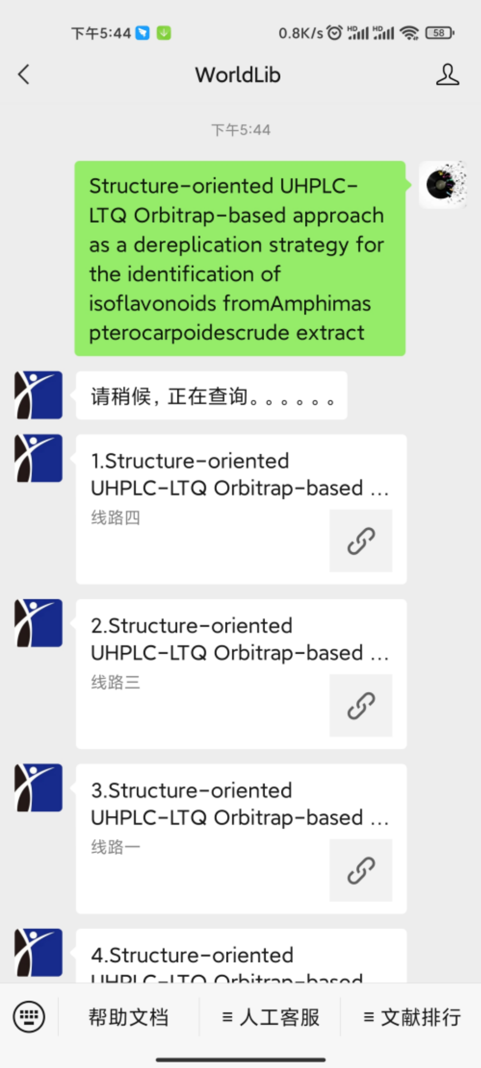

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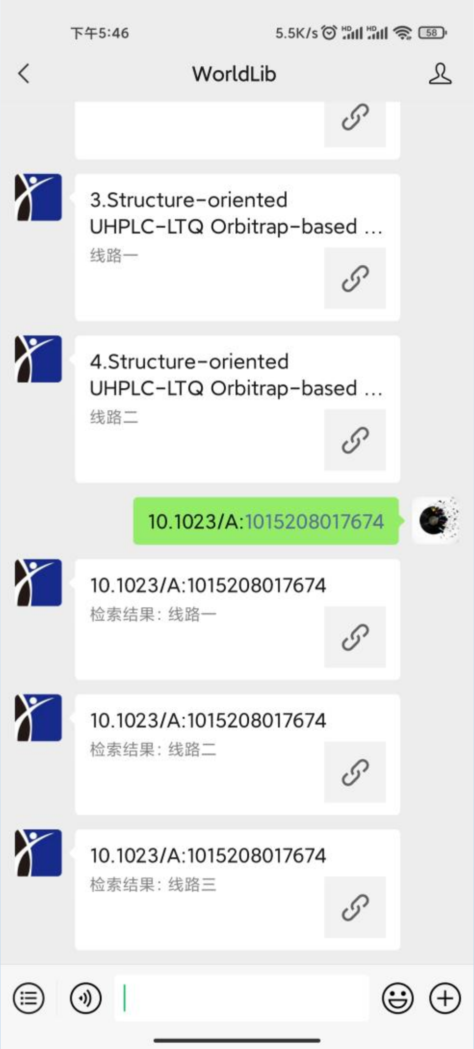

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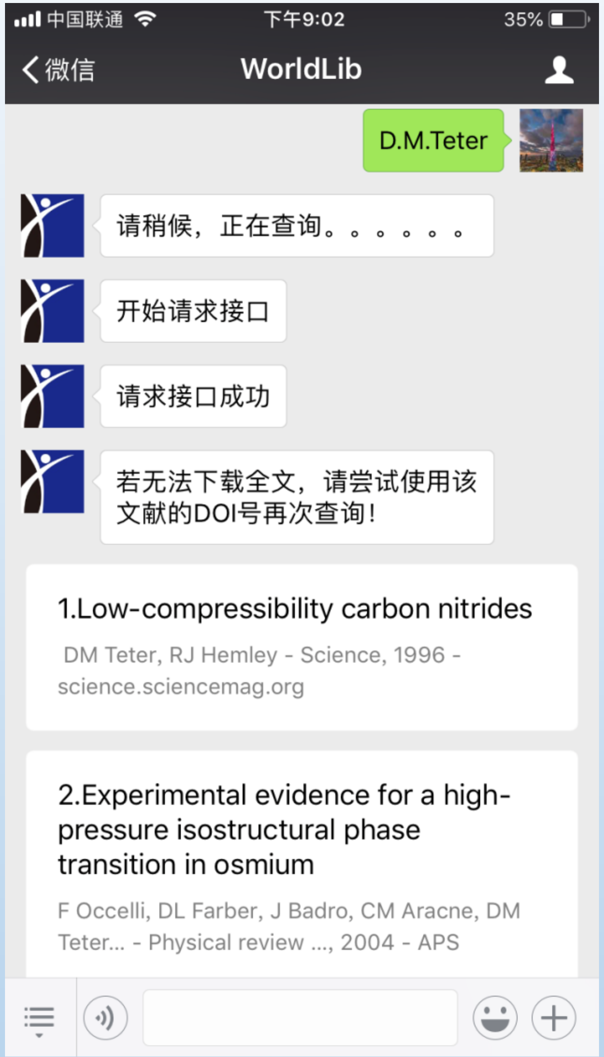

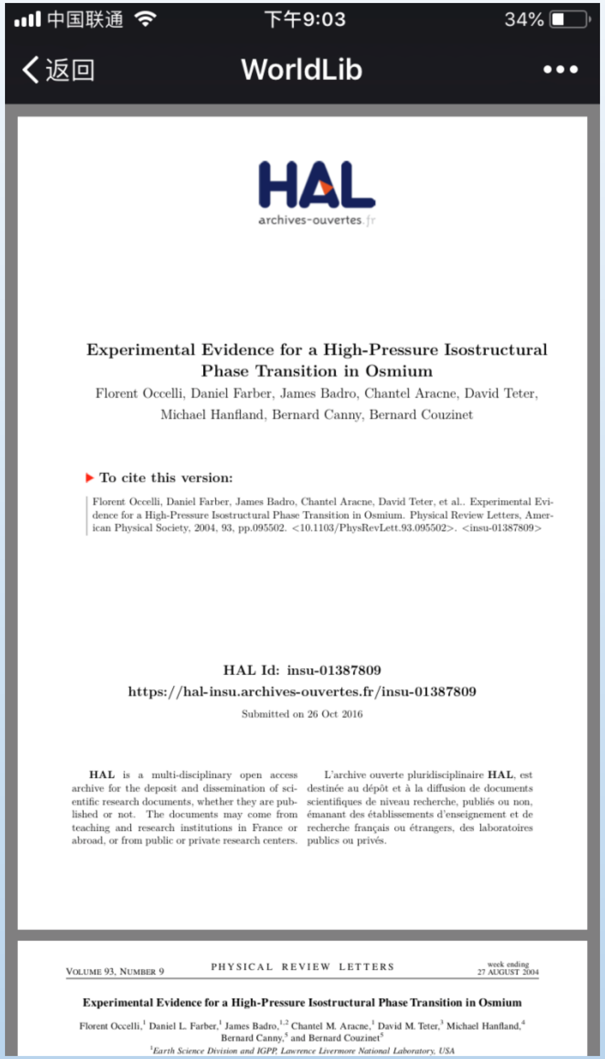

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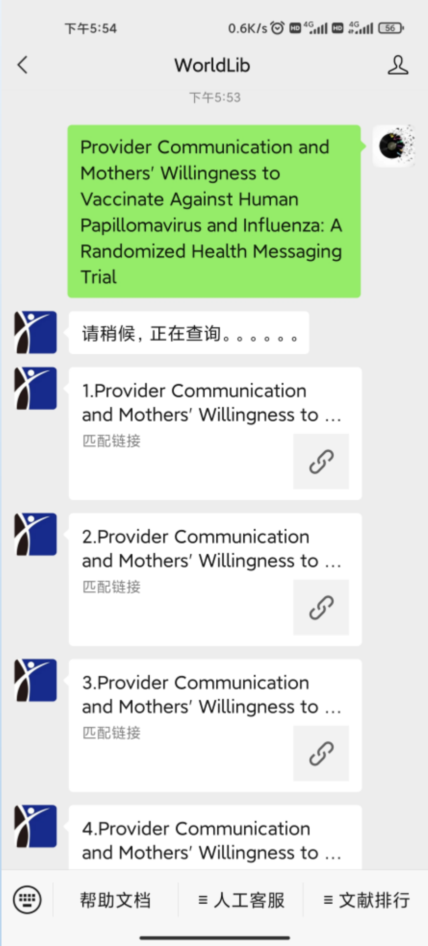

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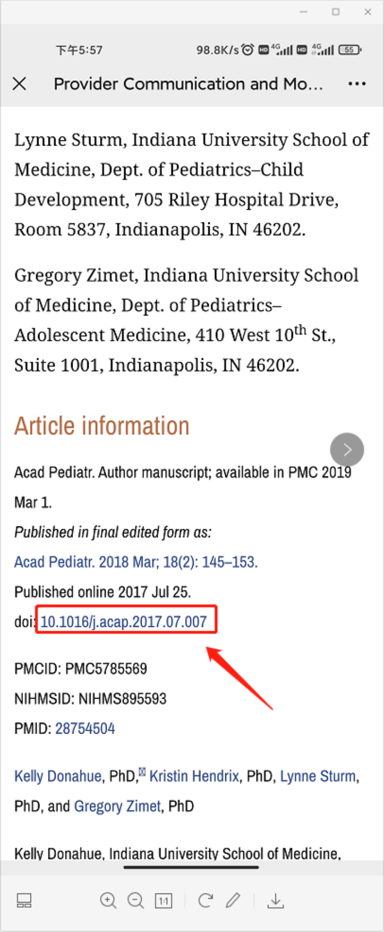

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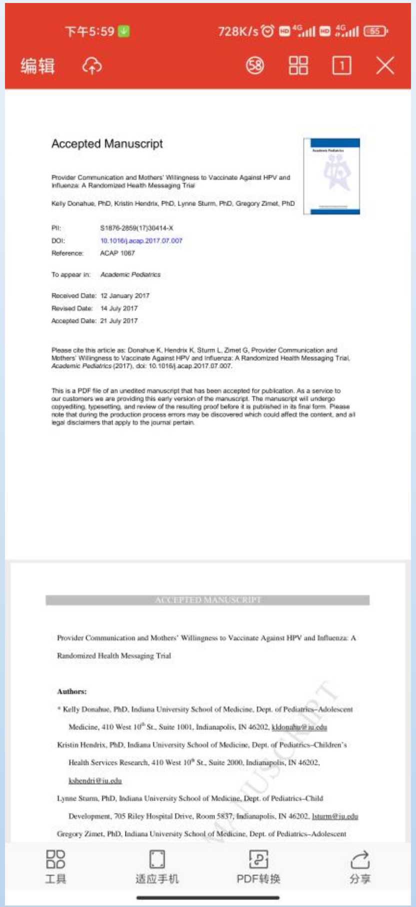

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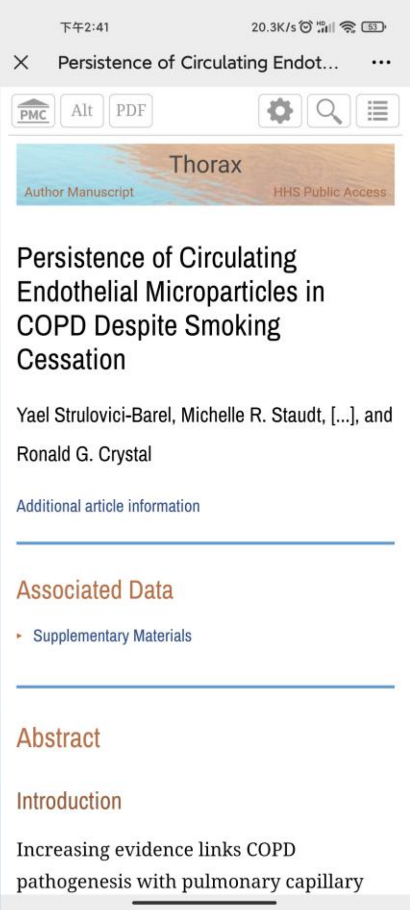

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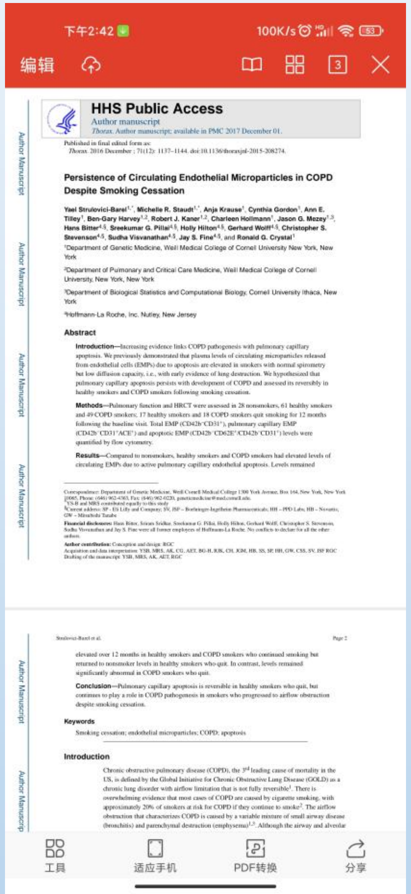

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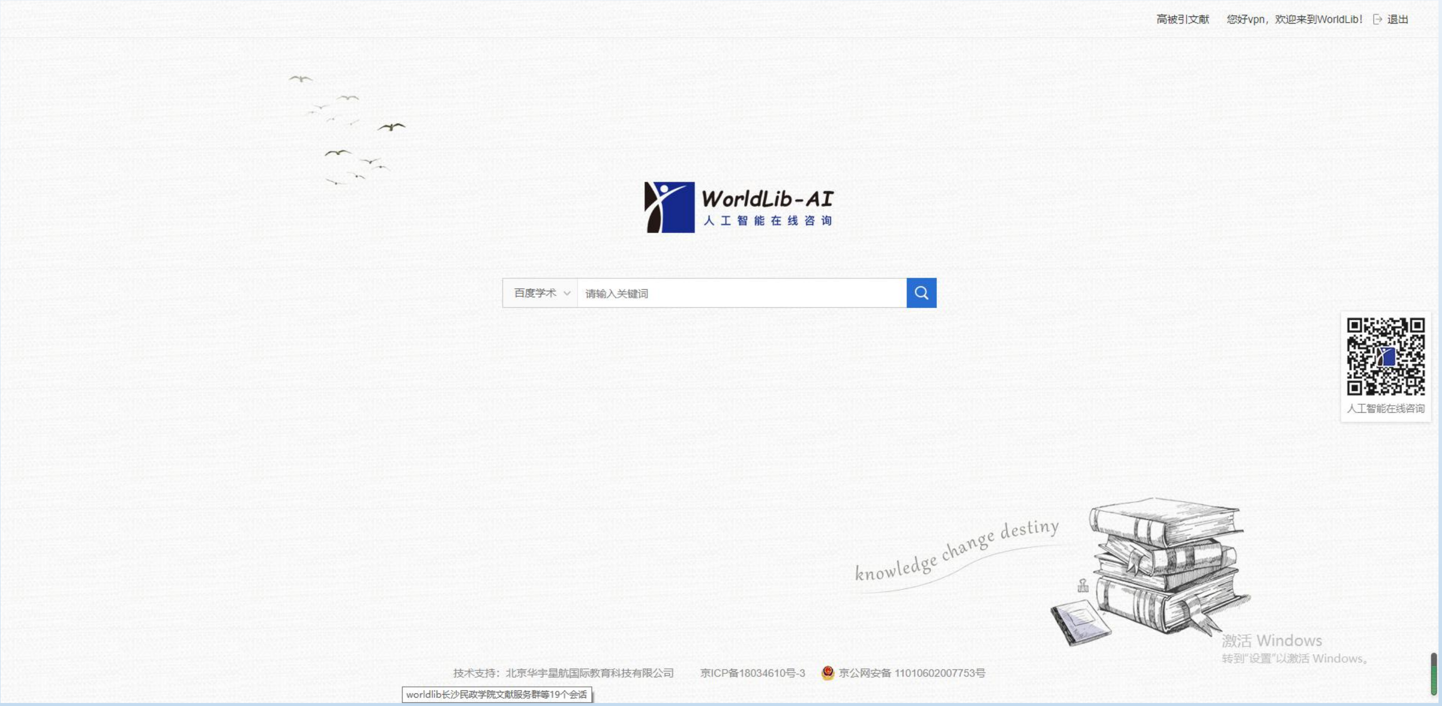

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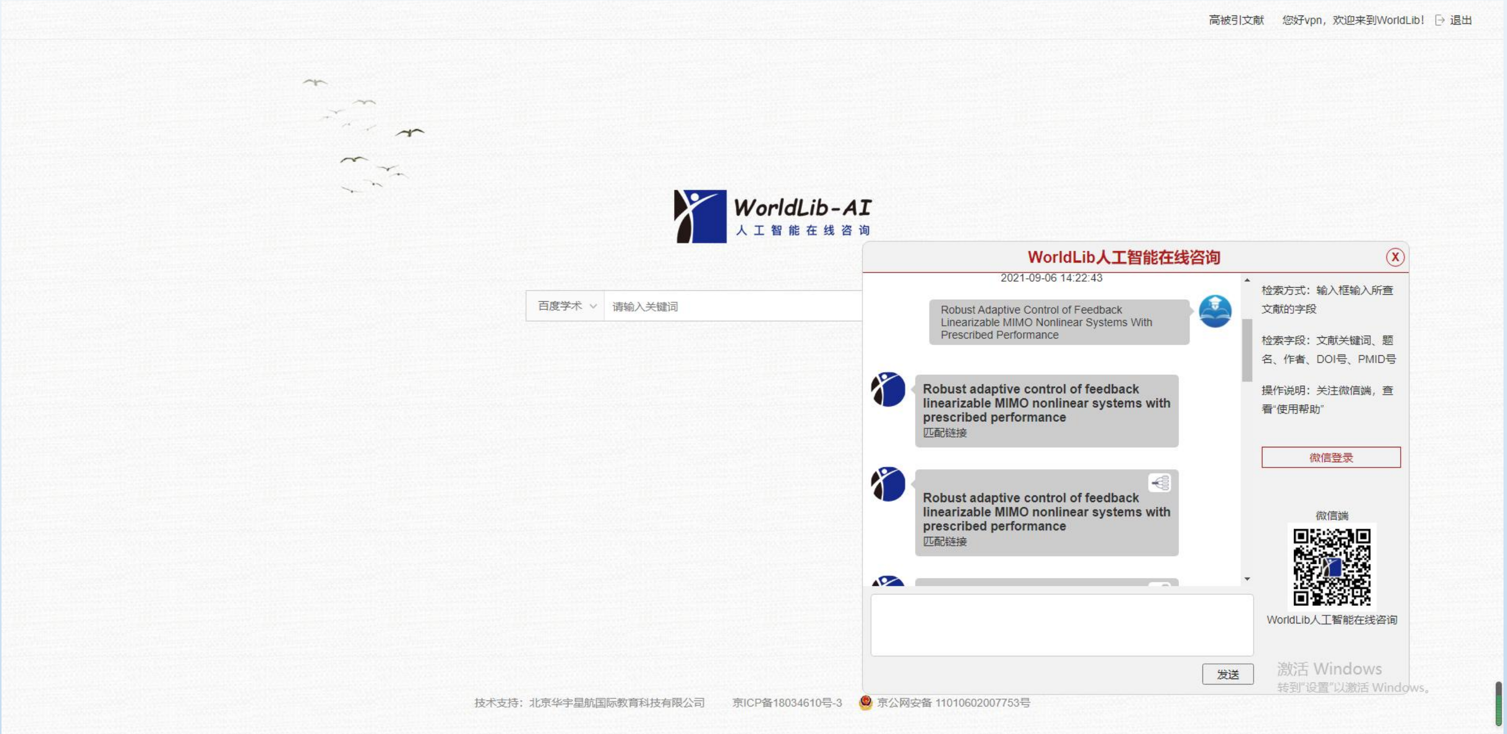

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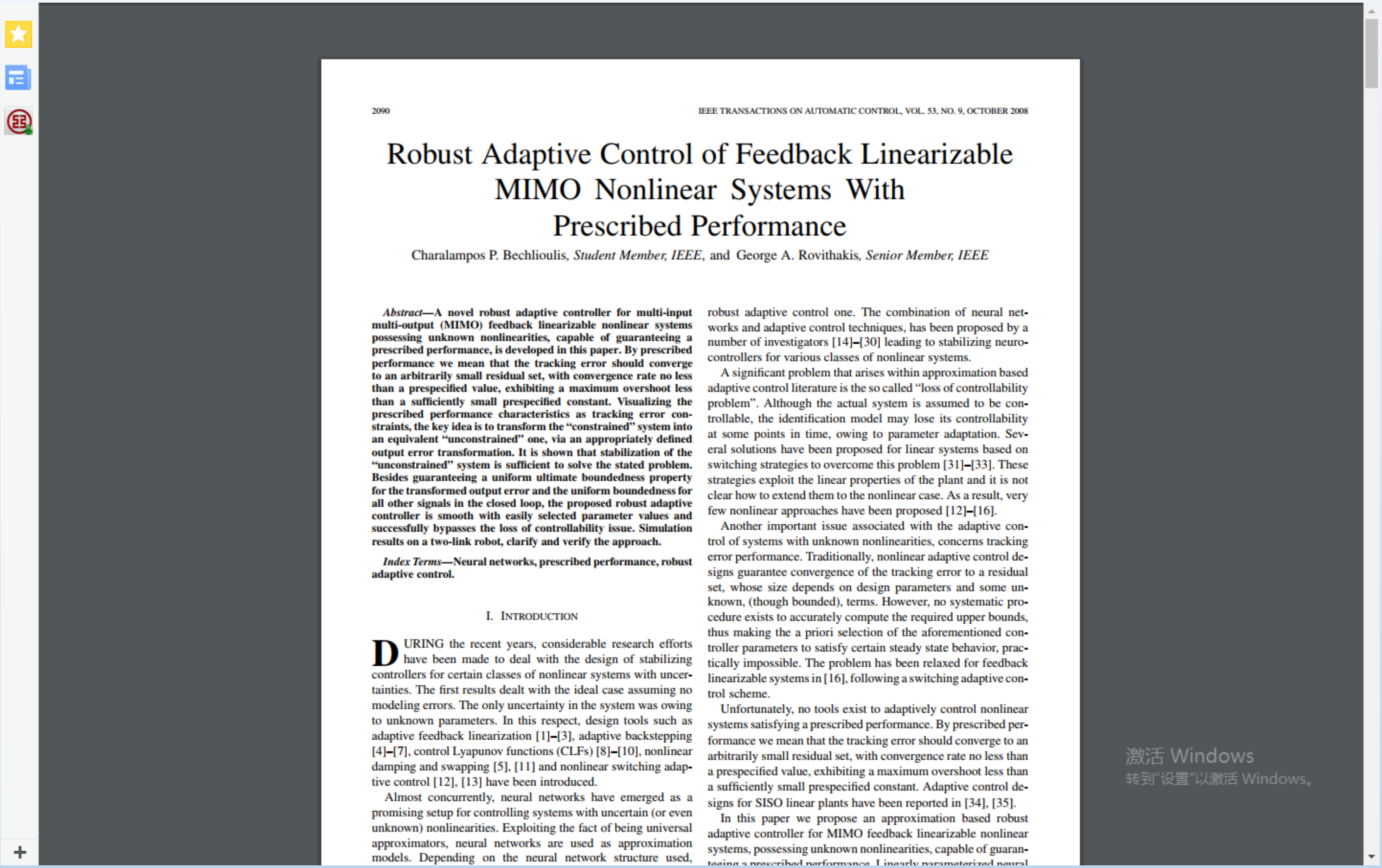

Robust Adaptive Control of Feedback Linearizable MIMO Nonlinear Systems With Prescribed Performance

Charalampos P. Bechlioulis, *Student Member, IEEE*, and George A. Rovithakis, *Senior Member, IEEE*

***Abstract*—A novel robust adaptive controller for multi-input multi-output (MIMO) feedback linearizable nonlinear systems possessing unknown nonlinearities, capable of guaranteeing a prescribed performance, is developed in this paper. By prescribed performance we mean that the tracking error should converge to an arbitrarily small residual set, with convergence rate no less than a prespecified value, exhibiting a maximum overshoot less than a sufficiently small prespecified constant. Visualizing the prescribed performance characteristics as tracking error constraints, the key idea is to transform the "constrained" system into an equivalent "unconstrained" one, via an appropriately defined output error transformation. It is shown that stabilization of the "unconstrained" system is sufficient to solve the stated problem. Besides guaranteeing a uniform ultimate boundedness property for the transformed output error and the uniform boundedness for all other signals in the closed loop, the proposed robust adaptive controller is smooth with easily selected parameter values and successfully bypasses the loss of controllability issue. Simulation results on a two-link robot, clarify and verify the approach.**

***Index Terms*—Neural networks, prescribed performance, robust adaptive control.**

I. INTRODUCTION

DURING the recent years, considerable research efforts have been made to deal with the design of stabilizing controllers for certain classes of nonlinear systems with uncertainties. The first results dealt with the ideal case assuming no modeling errors. The only uncertainty in the system was owing to unknown parameters. In this respect, design tools such as adaptive feedback linearization [1]–[3], adaptive backstepping [4]–[7], control Lyapunov functions (CLFs) [8]–[10], nonlinear damping and swapping [5], [11] and nonlinear switching adaptive control [12], [13] have been introduced.

Almost concurrently, neural networks have emerged as a promising setup for controlling systems with uncertain (or even unknown) nonlinearities. Exploiting the fact of being universal approximators, neural networks are used as approximation models. Depending on the neural network structure used, robust adaptive control one. The combination of neural networks and adaptive control techniques, has been proposed by a number of investigators [14]–[30] leading to stabilizing neurocontrollers for various classes of nonlinear systems.

A significant problem that arises within approximation based adaptive control literature is the so called "loss of controllability problem". Although the actual system is assumed to be controllable, the identification model may lose its controllability at some points in time, owing to parameter adaptation. Several solutions have been proposed for linear systems based on switching strategies to overcome this problem [31]–[33]. These strategies exploit the linear properties of the plant and it is not clear how to extend them to the nonlinear case. As a result, very few nonlinear approaches have been proposed [12]–[16].

Another important issue associated with the adaptive control of systems with unknown nonlinearities, concerns tracking error performance. Traditionally, nonlinear adaptive control designs guarantee convergence of the tracking error to a residual set, whose size depends on design parameters and some unknown, (though bounded), terms. However, no systematic procedure exists to accurately compute the required upper bounds, thus making the a priori selection of the aforementioned controller parameters to satisfy certain steady state behavior, practically impossible. The problem has been relaxed for feedback linearizable systems in [16], following a switching adaptive control scheme.

Unfortunately, no tools exist to adaptively control nonlinear systems satisfying a prescribed performance. By prescribed performance we mean that the tracking error should converge to an arbitrarily small residual set, with convergence rate no less than a prespecified value, exhibiting a maximum overshoot less than a sufficiently small prespecified constant. Adaptive control designs for SISO linear plants have been reported in [34], [35].

In this paper we propose an approximation based robust adaptive controller for MIMO feedback linearizable nonlinear systems, possessing unknown nonlinearities, capable of guaranteeing a prescribed performance. Linearly parameterized neural

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