prof. Ing. Ján Piteľ, PhD., Technical University of Košice, Faculty of Manufacturing Technologies, Department of Industrial Engineering and Informatics, Bayerova 1, 080 01 Prešov, Slovakia

REVIEWER REPORT
on PhD Dissertation Thesis

Author: **Ing. Peter Mark Beneš**

Title of Thesis: **Higher Order Neural Unit Adaptive Control and Stability Analysis for Industrial System Applications**

1. ACHIEVING THE OBJECTIVES OF THE DISSERTATION THESIS

The aims of investigations are clearly defined in chapter 3. The main objective of the dissertation work defined as the extension of a new framework for stability assessment of HONUs (Higher Order Neural Units), and their closed-loop stability has been successfully achieved. This main objective is supported by the fulfillment of five sub-objectives:
- Recalls the latest theories of HONUs and their fundamental learning algorithms presented in chapter 4.
- Transformation of nonlinear HONU architectures to a linearly approximated state-space model in discrete state points and development of the Discrete-time HONU Stability (DHS) condition described in chapter 6.
- The HONU polynomial equation's decomposition to sub-polynomial state-space form with the extension of HONU feedback control presented in chapter 7.
- Derivation of a new ISS based stability condition for BIBS (Bounded-Input-Bounded-State) stability assessment of HONU polynomial architectures termed as the Decomposed Discrete-time HONU Stability (DDHS) and described in chapter 7.
- Deep experimental analysis and comparison of the derived DHS and DDHS approaches with respect to Lyapunov control function stability approach presented in chapter 8 also using knowledge concerning HONU-MRAC control loop design for real industrial applications described in chapter 5.

2. ANALYSIS OF CURRENT STATE OF THE ART

In the dissertation thesis, there is presented an excellent analytical review of the current state of the art based on 86 cited publications. In the Introduction, there are summarized existing state-of-the-art process identification and control approaches and setup the direction for deeper study of computational intelligence based methods and adaptive polynomial neural network-based architectures. A nice overview of the methods and problems in adaptive control is in chapter 2, where control input adjustment methods, heuristic tuning based methods, and parameter adjustment based control such as neural network and fuzzy-based methods are presented.

3. THEORETICAL CONTRIBUTIONS OF THE DISSERTATION THESIS

The main theoretical contributions of the dissertation thesis are two novel methodologies for stability analysis of nonlinear control loops with HONUs. They have been theoretically derived and validated by simulation in chapters 6 and 7 and by experimental analysis in chapter 8. The

first one named DHS was proved to be an effective method for concluding BIBO (Bounded-Input-Bounded-Output) stability of a HONU model, or further HONU-MRAC closed control loop. The second named DDHS was developed for evaluating the local BIBO stability, or further BIBS stability of a HONU-MRAC closed control loop maintains dynamical stability along its trajectory in state-space. The suggestions for the next research direction outlined in chapter 10 can also be considered as a theoretical contribution of the dissertation thesis.

4. PRACTICAL CONTRIBUTIONS OF THE DISSERTATION THESIS

The dissertation's main practical contribution is validating two novel real-time BIBO/BIBS-based stability evaluation methods for HONUs and their closed control loops through various nonlinear system examples and new results presented from the rail automation field for real-time industrial process control via HONU-MRAC design. BIBO/BIBS stability is very useful in practical control applications where it is often necessary and more practical to ensure that the process states are bounded with respect to bounded process inputs supplied to the engineering process.

As a further practical outcome of the dissertation thesis is the ASPI Kit software and stability analysis library in the programming language Python software to help engineers and practitioners investigate the potentials of HONU adaptive identification and control for their respective engineering applications.

5. SOLUTION METHODS USED, THEIR APPLICATION AND KNOWLEDGE LEVEL

Following the comprehensive review of state-of-the-art adaptive control approaches and further the review of suitable stability analysis method, the author proposed novel nonlinear time-variant state-space representations of HONUs with extension them to control loops with possible real-time adaptation. The author properly applied advanced methods based on computational intelligence and the common Lyapunov approach for analysis and synthesis of automatic nonlinear control, including validation by simulation and real experiments. The obtained knowledge during research has been presented in 21 publications (more than half as the first author), including international journals, book chapters, and scientific conferences. Further directions of research proposed by author via an introduction of sliding mode control using the decomposed HONU method and extension of the DHS and DDHS approached to other polynomial based neural architectures also confirm author's ability to work scientifically in the field of Technical Cybernetics.

6. FORMAL COMMENTS ON THE DISSERTATION THESIS

The dissertation thesis is divided into 13 chapters, including Introduction, Conclusion, Literature, and Appendix in the total number of pages 134. The thesis also includes a separate Summary. The formal level of the dissertation thesis is good, the dissertation thesis is very well legible without significant formal shortcomings.

Comments:

a) Not all symbols and abbreviations are in Nomenclature or List of Abbreviations, respectively.

b) It would be better to start a new chapter on a new page.

c) Page 37: It would be useful to use an index for "$\tilde{y}$" in Eq. (1) and (2) to distinguish between QNU and CNU.

d) Page 53: The same symbol "r" used for the desired value as on page 37 for the order of polynomial nonlinearity.

e) Page 59: Bad reference to Table 8.

f) Pages 104, 105, 108: Some units are in italics, the symbol for time is not in italics.

g) Page 119: Coefficient terms $\hat{\beta}_i$ are not in Eq. (154).

h) Page 124: DHS method is mentioned twice instead of DDHS in the sentence "Following from the reviewed concepts of discrete-time model and state-of-the-art neural networks stability theories, the DHS and DHS method serves as…".

i) Reference [3] seems to be uncompleted.

7. QUESTIONS AND REMARKS

a) There is written on page 37: „Throughout this dissertation, the term "low to moderately nonlinear" refers to dynamic systems that can be approximated by a given order of polynomial nonlinearity i.e. r.". What is considered as a maximum value of r for low to moderately nonlinear system?

b) Please explain Figure 9.

c) Does Figure 15 illustrate a mathematical model as it is written in the text?

d) What is a role of PI controller in Figure 28?

8. CONCLUSION

Although advanced algorithms exist and are quite well theoretically proven also for neural network-based control, there is still a gap in physical implementation within the real industry. From this point of view, the reviewed thesis titled „Higher Order Neural Unit Adaptive Control and Stability Analysis for Industrial System Applications" is an important contribution to the further development of science and technology in the research field of interest.

The author Ing. Peter Mark Beneš has proven the ability to scientifically work and creatively solve complex research problems, so I **recommend** to defend his dissertation thesis.

In Prešov, April 14, 2020

prof. Ing. Ján Piteľ, PhD.
Reviewer