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Assessment of Ph.D. Thesis

Nonlinear Optimal Control System Synthesis for Dynamically Coupled Autonomous Aerial Vehicles

CANDIDATE: Ing. Jiří Novák

EVALUATOR: Prof. Hugh HT Liu, Ph.D. P.Eng. F.CAE, F.EIC, F.CSME, AF.CASI, AF.AIAA

1. Objectives / State of the Art

The surge in state-of-the-art machine learning and optimization techniques can be attributed to the rapid advancements in computational power and miniaturization of embedded computers. In various industrial applications, the utilization of these techniques has emerged as a practical and preferred choice.

Guidance, Navigation, and Control (GNC) techniques play a crucial role in enabling autonomy for both aerial and ground vehicles. The development of GNC algorithms is predominantly based on a model-based design approach, which emphasizes explainable and verifiable solutions.

The increasing requirements and dynamically changing environments challenge the current state-of-the-art GNC approaches, prompting the adoption of data-driven and adaptive systems. Integrating these systems into safety-critical applications presents the challenge of developing protective mechanisms and conducting thorough verification and validation procedures.

Mr. Novák aims to develop, implement, and validate a GNC system for an Unmanned Aerial Vehicle (UAV) adapted for aerial grasping missions. The system will incorporate elements of optimal control and machine learning to ensure robust, explainable, and safe control. Mr. Novák proposes a statistics-based approach using surrogate modeling techniques for safety validation, treating the system as a black-box. Assessing the probability of system failure is crucial for real-world integration efforts necessitating certification by relevant regulatory authorities.

2. Innovation and Originality / Documentation of the Relevance

Currently, further development and use of statistical approaches in the certification of autonomous platforms is expected with respect to the development of machine learning systems that are not classically programmed, thus requiring a different approach in the demonstration of their functionality and properties.

Mr. Novák's thesis specifies and thoroughly investigates multiple relevant research objectives related to the design and development of the GNC system for aerial manipulation missions of UAVs. The author proposes a Nonlinear Model Predictive Control (NMPC) approach and explores the benefits of a coupled control mechanism over a decoupled one. To accomplish this, Mr. Novák employs a variety of numerical solvers and studies their appropriate parameterization and the structure of the objective function.

Additionally, for system robustness, an adaptive control loop is integrated into the initial NMPC. Mr. Novák introduces several innovations in the proposed approach that have a significant impact on the rapidly growing UAV sector. The findings of the thesis can also be applied to space applications where the complex dynamics of coupled multi-body systems often present challenges.

The author's proposed validation methodology is solid and includes evaluation of designed kinematic metrics, testing of the developed system on high-fidelity models in comparison to the simpler UAV abstractions often found in literature, and the use of statistical models to assess operational risks in relation to environmental uncertainties.

Mr. Novák proposes a Reinforcement Learning (RL) approach for adaptive NMPC objective weighting. This contribution is highly original as it requires significantly fewer training samples and addresses issues that may arise when using multi-objective cost functions. The analysis of uncertainties in the optimization process, driven by the Cross-Entropy Method (CEM) using Polynomial Chaos Expansion (PCE) surrogate models, also extends the capabilities of the original method in a novel manner. Overall, the thesis's objectives are clearly stated and rigorously achieved.

3. Methodology / Solution Strategy

As a prerequisite to nonlinear optimal control solutions for dynamically coupled autonomous aerial vehicles, Mr. Novák summarizes the theoretical basis of mathematical optimization and its application to optimal control problems, including various numerical examples showcasing possible applications in the unmanned aerial vehicles domain, with emphasis on computationally efficient methods for solving nonlinear optimization problems and assessing computational performance on the state of the art embedded platforms.

Additionally, Mr. Novák introduces the concept of modeling multi-rotor drones using fundamental principles of physics, extending to the kinematic and dynamic model of an integrated robotic arm, and designing a GNC system based on a predictive control method augmented by an adaptive feedback loop to maintain control even in the presence of uncertainties arising from the environment or disparities between real and virtual dynamic models.

To address combinatorial and continuous optimization, Mr. Novák, introduces cross-entropy based approach, which is particularly suitable for black-box models where the calculation of partial derivatives at the solution points is not considered. He then extends the basic cross-entropy method to include simultaneous system validation using a surrogate model that approximates the probability of system failure at the design point.

Mr. Novák tests his designs using numerical experiments. Initially, the drone is tested using predictive control and an adaptive loop augmentation. Then, the evaluation continues with predictive control of the robotic arm. Finally, the drone with an integrated robotic arm undergoes testing with a fully coupled control system, where the drone and the robotic arm are not controlled independently, but in a coupled manner, unlike similar coupled motion platforms.

Additionally, Mr. Novák conducted a flight experiment with an unmanned drone equipped with an actuated tank and a single degree of freedom moving arm. This drone is capable of in-flight fluid transfer from the on-board tank using the movable arm.

4. Quality of the Results / Perspectives for Application

Mr. Novák's thesis addresses the challenges associated with the safe deployment of optimization-based and adaptive algorithms for UAV applications. The thesis introduces a comprehensive platform that integrates a UAV with a robotic arm, specifically designed for missions involving physical interactions with the environment. The research demonstrates the benefits of coupled control, including improved coordination and efficiency in mission tasks.

Extensive numerical experiments were conducted on the coupled system. Initially, the problem was simplified by focusing solely on the arm kinematics, neglecting the coupling effects resulting from arm movement, changes in moments of inertia, and the total mass of the UAV when grasping an object. Subsequently, the study investigated the impact of model mismatch caused by coupling effects on the performance of NMPC. The thesis also proposed a neural network architecture to drive the NMPC parameters, and the weight-varying NMPC demonstrated superior performance compared to the baseline NMPC across presented kinematic evaluation metrics.

Mr. Novák's ability to anticipate and address complex issues showcased his multidisciplinary understanding of the problem. The in-depth nature of the full solution underscores the exceptional mentoring provided by Professor Chudý at the AeroWorks laboratory.

5. Appearance and Form of the Thesis

The submitted thesis is effectively structured into six well-defined chapters, each containing coherent content and seamless transitions between them. The language used is clear, understandable, and grammatically accurate. Additionally, the thesis includes abstracts in both English and Czech, acknowledgements, a list of figures and tables, references, and appendices that cover essential concepts integral to the thesis, along with a list of the hardware components utilized in constructing the drone for the flight experiments. All presented results are thoroughly explained, and the corresponding references are accurately cited. The thesis fully meets the requirements expected of a dissertation work.

6. Resonance in Relevant Communities

Mr. Novák is the main author and co-author of 11 topic relevant publications. Some of these publications were submitted and accepted in 2024. The majority of these publications are listed in Scopus or Web of Science. The core content of the thesis has been presented at distinguished aerospace and computer science conferences.

Additionally, Mr. Novák has been involved in several industrial projects relevant to the thesis topic, which have led to impactful technical solutions. Moreover, through international collaboration with Technion, the Israel Institute of Technology, Mr. Novák conducted research and achieved novel results in derivative-free optimization techniques and their application in allocation tasks in aerospace.

7. Grading of the Thesis

Mr. Novák's contribution and work align perfectly with the current challenges in Unmanned Aerial Vehicle applications and adoption of Machine Learning algorithms in Guidance, Navigation and Control systems. His thesis demonstrates deep theoretical understanding, complemented by experience gained from working on industrial research projects. This has led to exceptional results that surpass the current state-of-the-art in Nonlinear Model Predictive Control techniques and their implementation for complex multi-degree-of-freedom aerial manipulation. Furthermore, Mr. Novák's work takes into account operational constraints, onboard optimization computational limits, and hyperparameter selection, among other factors.

I grade the thesis as

"**Excellent**" (summa cum laude)

I do recommend continuation of the Ph.D. degree examination process.

Toronto, September 7th, 2024

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