

Doctoral thesis (hereinafter referred to as "thesis"), title of the thesis:

Nonlinear optimal control system synthesis for dynamically coupled autonomous aerial vehicles

Name of the doctoral student (hereinafter referred to as "student"), name and surname:

Jiri Novak

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I. Thesis

Appropriateness and relevance

The topic of the thesis falls into the area of automation and robotics, which is a very active research field with many contributions and new innovations. The field is dynamically evolving, especially in the field of unmanned aerial vehicles (UAV). This is where the thesis contributes to. The thesis addresses the difficult task to automatically control a UAV with a robotic arm mounted on it in order to fulfill certain grasping tasks. This setting is fundamental and highly relevant to future technologies for automatic inspection and manipulation. Closely related tasks can be found also in new space applications, e.g., in-orbit servicing or space debris removal tasks. The challenge is to control the complex and highly nonlinear coupled system of UAV and robotic manipulator in a reliable, robust, and efficient way. Standard control techniques based on linearization are not sufficient anymore to handle the complex motion and to obey constraints. The proposed approach in the thesis is suitable to achieve this goal. The approach combines a modern optimization-based control technique, that is, model-predictive control, with machine learning techniques to adapt control parameters in a state-dependent way with the aim to obtain a more robust controller. The proposed control concept is innovative and relevant and not limited to the specific application in the thesis.

A summary of the contributions of the thesis

The goals of the thesis are

- Derivation of a mathematical model for grasping tasks of a UAV with a mounted robotic arm
- Implementation of a simulator taking into account uncertainties
- Application of a model-predictive control scheme for automated grasping tasks
- Assessment of failure regions
- Setting up a laboratory experiment

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With these goals the thesis aims at a holistic system evaluation for defined flight maneuvers. This goal was fully achieved within a simulation environment. To this end, a detailed mathematical model for the dynamics of the UAV and the robotic arm was developed and implemented in a simulation environment. Herein, the model was augmented by external uncertainties, in particular wind, gusts, and aerodynamic ground effects. In total, a very realistic simulation environment was created.

A new adaptive model-predictive control algorithm was developed. Herein, a (standard) nonlinear model-predictive controller was augmented by a component, which adapts control parameters as a function of the current state using a neural network, which was trained by a reinforcement learning mechanism. It was shown that the adaptive version increases robustness and performance of the controller.

A major contribution of the thesis is the development of a methodology for the assessment of safe operational domains under parameter uncertainties. Herein, several statistical methods are combined in a clever way to predict failure regions of the controller. In particular, the cross entropy method is combined with polynomial chaos expansion and kriging leading to the RBCE method.

The last (minor) goal with setting up a laboratory experiment was partly achieved from my point of view. A UAV was designed using a Raspberry Pi microcomputer and a Pixhawk flight controller. Hence, the technical setup is available, but only basic flight experiments were conducted as far as I could see. The transfer from computer simulations to real flight tests is a time consuming process, though, and it is beyond a realistic expectation that the whole process chain from model building to experiments with a prototype can be realized in a single thesis. From my point of view the ambition and efforts to practically realize the control task has to be seen very positive. With this thesis the foundations for this endeavor is created and can be explored in future works.

Without doubts Jiri Novak contributed substantially to all these achievements and created a valuable and impressive toolchain.

Novelty and significance:

The single building blocks of the developed control concept, that is, model-predictive control (MPC), polynomial chaos expansion (PCE), kriging, reinforcement learning (RL), and cross entropy method (CEM), were known in the literature, but the proper combination of these blocks in an integrated control architecture is the novelty of the thesis from the methodological point of view. The overall control architecture together with the tool for the determination of a safe operation domain is not restricted to the specific application considered in the thesis. It is a rather general concept, which can be transferred to essentially any optimization-based control task.

The detailed investigation of grasping tasks with UAVs and mounted robotic arms is a novelty from a technical point of view. The thesis lays the foundation for future practical flight tests and opens the door for a potential commercial exploitation. As a side product the thesis provides a realistic simulator for a UAV, which is generally useful for a variety of investigations.

Evaluation of the formal aspects of the thesis:

The thesis is very well structured and the content is arranged in a logical and meaningful order. The language level is excellent. The presentation of the material is clear and precise, the illustrations are

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appropriate and helpful. The list of references is up to date and conveys a good and broad overview on the topic.

Quality of publications

The core contributions of the thesis have been published in a sequence of papers (11 papers in total, 3 published, 8 accepted). This has to be considered a high number of publications. One paper was accepted by the Journal of Aerospace Information Systems, most of the other papers appeared in the proceedings of established conferences in the field of avionics, that is, the DASC conference (3 papers), ICAS (4 papers) or AIAA Aviation Forum (1 paper). Two papers appeared in a book series on Machine Learning, Optimization, and Data Science by Springer. The contents of the thesis fit perfectly into the scope of the chosen publication organs and I am sure the publications will receive a good visibility in the future.

II. Student's overall achievements

Overall R&D activities evaluation:

The high quality of the thesis, the high number of publications, and the participation in various funded projects clearly shows that Jiri Novak is a very active researcher with a genuine interest in scientific work. With his contributions he has proven the ability to work at a high scientific standard. He is able to master challenging tasks and to find a feasible and effective way to solve the problems. Furthermore, he combines research tools in a creative way and evaluates his results carefully and systematically. His work spans a wide range from simulations to technical realization and covers control techniques, estimation methods, machine learning, and optimization.

III. Conclusion

In summary, the thesis is very well written, satisfies high scientific standards, and addresses a relevant and challenging problem class. In his thesis Jiri Novak applies modern model-predictive control and estimation techniques for grasping tasks with a UAV and advances the state-of-the art with very good results. With his thesis he shows the ability to work on a high scientific level. Without any reservations I recommend to accept the thesis and to proceed with its defense. It meets the generally accepted requirements for the award of an academic degree in accordance with Section 47 of Act No. 111/1998 Coll., on higher education institution.

Neubiberg, 10.09.2024

Signature of the reviewer: