SUPERVISOR'S OPINION OF FINAL THESIS

I. IDENTIFICATION DATA

Thesis name:	**An Improved RRT* Algorithm for Multi-Robot Path Planning**
Author's name:	**Poludin Mikhail**
Type of thesis :	bachelor
Faculty/Institute:	Faculty of Electrical Engineering (FEE)
Department:	Department of Cybernetics
Thesis supervisor:	Tiago Pereira do Nascimento
Supervisor's department:	Department of Cybernetics

II. EVALUATION OF INDIVIDUAL CRITERIA

Assignment **ordinarily challenging**

Evaluation of thesis difficulty of assignment.

The thesis assignment to the student is considered ordinarily challenging. The challenge here is, despite the algorithmic contribution itself, the need to implement the contributions on real robot experiments, using real UAVs. The student must use one autonomous UAVs and perform a successful experiment in a GNSS-denied environment. This usually is very time consuming and technically demanding.

Satisfaction of assignment **fulfilled**

Assess that handed thesis meets assignment. Present points of assignment that fell short or were extended. Try to assess importance, impact or cause of each shortcoming.

My evaluation is that this thesis meets the requested assignment.
None of the required tasks from the final assignment fell short. The student considered fixed obstacles, GNSS-denied environment, performed simulation o a multi-robot scenario application, performed real robot experiments and comparisons with the state-of-the-art approaches.

Activity and independence when creating final thesis **A - excellent.**

Assess that student had positive approach, time limits were met, conception was regularly consulted and was well prepared for consultations. Assess student's ability to work independently.

My evaluation is that the student performed an excellent job in his thesis.
The student was under my supervision only in this semester, so he had to come up with the work from scratch. He was able to implement two well known algorithms (RRT and RRT*), expand the approach for a 3D search, analyze the algorithms behavior with obstacle avoidance, and was able to expand the RRT* to a multi-robot application. The student always came prepared to the biweekly meeting I have with him and other students under my supervision. He was able to work independently and search for answers beyond my orientation. He also participated in a two week experimental campaign the MRS group performed in April at CVUT TEMEŠVÁR.

Technical level **B - very good.**

Assess level of thesis specialty, use of knowledge gained by study and by expert literature, use of sources and data gained by experience.

My evaluation is that this thesis has a very good technical level.

This thesis includes a brief overview of the UAV path planning and a detailed explanation of the algorithms implemented. The implementation of the RRT and RRT* algorithms were performed and extended to handle the generation of trajectories for multiple drones. Two obstacle avoidance approaches were introduced and tested with both RRT family

path-planning algorithms. Experiments of autonomous UAV flight in a forest-like environment were conducted in both simulation and real world. Both simulations and real world experiments were filmed. Thus, the student demonstrated good use of the knowledge in path-planning, and deployment of UAVs in a real world scenario. The comparison using the state-of-the-art RRT algorithms also demonstrated a thorough research from the literature.

Formal and language level, scope of thesis **C - good.**

Assess correctness of usage of formal notation. Assess typographical and language arrangement of thesis.

The student has a good written English. However, I feel that the student could have used better notations and formulate a problem in a better manner. The final version of the thesis, however, is still good enough for a bachelor degree graduation in my evaluation,.

Selection of sources, citation correctness **C - good.**

Present your opinion to student's activity when obtaining and using study materials for thesis creation. Characterize selection of sources. Assess that student used all relevant sources. Verify that all used elements are correctly distinguished from own results and thoughts. Assess that citation ethics has not been breached and that all bibliographic citations are complete and in accordance with citation convention and standards.

The student performed a good job on selecting the references. The student acquired 33 references. I believe he could have got more. The quality could also be improved.

Additional commentary and evaluation

Present your opinion to achieved primary goals of thesis, e.g. level of theoretical results, level and functionality of technical or software conception, publication performance, experimental dexterity etc.

The main objective of the thesis was achieved. The student compared and implemented algorithms from the RRT family for the exploration of GNSS-denied environments with obstacle. The student also performed real robot experiments and numerical comparisons with the state-of-the-art approach. The software used is available on Github and can be used in other projects. All the work was performed with a rigorous scientific methodology and the date is sufficient, in my opinion, for the graduation as a Bachelor.

III. OVERALL EVALUATION, QUESTIONS FOR DEFENSE, CLASSIFICATION SUGGESTION

Summarize thesis aspects that swayed your final evaluation.

In summary, my evaluation was due to the fact that the student:

1. Performed improvements and comparison with the RTT state-of-the-art algorithms.
2. Performed real robot experiments.

I evaluate handed thesis with classification grade B - very good.

Date: **25.5.2022** Signature:

THESIS REVIEWER'S REPORT

I. IDENTIFICATION DATA

Thesis title:	An Improved RRT* Algorithm for Multi-Robot Path Planning
Author's name:	Poludin Mikhail
Type of thesis :	bachelor
Faculty/Institute:	Faculty of Electrical Engineering (FEE)
Department:	Department of Cybernetics
Thesis reviewer:	Ing. Jakub Sláma
Reviewer's department:	Department of Computer Science

II. EVALUATION OF INDIVIDUAL CRITERIA

Assignment **ordinarily challenging**

How demanding was the assigned project?

The goal of this thesis is to plan collision-free trajectories for multiple UAVs. Each UAV must avoid other UAVs and fixed obstacles present in the environment. The proposed solution is required to be based on well-known RRT and RRT* algorithms. Performance evaluation, comparison of multiple possible approaches, and real deployment are also required. Since the required features of the thesis are based on well-established algorithms and the complexity of the required extension is not constrained, I evaluate the assignment as ordinarily challenging.

Fulfilment of assignment **fulfilled with minor objections**

How well does the thesis fulfil the assigned task? Have the primary goals been achieved? Which assigned tasks have been incompletely covered, and which parts of the thesis are overextended? Justify your answer.

The desired path planning algorithms RRT and RRT* have been implemented, and their performance has been evaluated; however, I would expect a more thorough evaluation of the performance. The desired extension for multiple UAVs has been proposed. Unfortunately, the experimental deployment has been performed only for a single UAV instead of multiple UAVs as required in the assignment, and the reasons for that are not elaborated.

Methodology **correct**

Comment on the correctness of the approach and/or the solution methods.

Although the author tries to support his work with literature, the literature review could be more thorough, other possible approaches could be presented to readers, and the selections of methods could be explained more. Even though this makes it quite hard to follow the author's reasoning for decisions and selected approaches, the selections are correct and well suited to the thesis goal.

Technical level **D - satisfactory.**

Is the thesis technically sound? How well did the student employ expertise in the field of his/her field of study? Does the student explain clearly what he/she has done?

Overviews of other possible approaches than the selected ones (for example, for the multi-UAVs extension of the RRT algorithm) are often missing or insufficient. Therefore, it is not clear if the author looked up possible approaches and selected the most suitable one/selected one based on some criterion or if the first suitable approach has been selected as the reasoning for the selections is absent or rather shallow. Furthermore, a significant part of the thesis consists of describing well-known approaches, such as the RRT algorithm, and evaluating their performance. Since the approaches are well-established and commonly used, the performance evaluation could be more thorough and detailed to show the author's understanding of the selected methods. Other errors are also present, e.g., in (9.2), where the distance to an obstacle measured by Lidar is considered as a distance to the center of the obstacle.

Formal and language level, scope of thesis **E - sufficient.**

Are formalisms and notations used properly? Is the thesis organized in a logical way? Is the thesis sufficiently extensive? Is the thesis well-presented? Is the language clear and understandable? Is the English satisfactory?

Although intentions can be seen in the text, the thesis structure is not very good, making it difficult to follow the author's motivation, ideas, and decisions. Topics such as the evaluation of discussed methods are often found in various parts of the

thesis instead of a single coherent section. On top of that, many simplifying assumptions and reasonings are missing in the text, remaining hidden for the reader and making it very difficult to follow the author. The text contains many irrelevant details, such as in which function a particular feature is implemented, even though it is not further used in the text, and the key message, such as why that feature is important or how the resulting behavior is really achieved are missing. Undefined symbols and inconsistent notations are also common, especially in pseudocodes. The same inconsistency applies to formal things such as numbering subchapters, referencing figures and algorithms, etc.

Selection of sources, citation correctness **D - satisfactory.**

Does the thesis make adequate reference to earlier work on the topic? Was the selection of sources adequate? Is the student's original work clearly distinguished from earlier work in the field? Do the bibliographic citations meet the standards?

The thesis has a significant number of sources (33). Nonetheless, sometimes it is unclear if the author is using only cited ideas or quoting parts of cited work (see Fig. 4.1 and [27]). Moreover, citations are sometimes incomplete (see [13]) and inconsistent (see [11] and [13]). Last but not least, citations of web pages are missing key aspects such as date of access.

Additional commentary and evaluation (optional)

Comment on the overall quality of the thesis, its novelty and its impact on the field, its strengths and weaknesses, the utility of the solution that is presented, the theoretical/formal level, the student's skillfulness, etc.

The thesis focuses a lot on irrelevant particularities, e.g., on which ROS topic data are published, instead of focusing on the high-level ideas and details of the proposed solution, such as how the desired behavior is achieved, why is it important, or why this particular approach has been selected.

III. OVERALL EVALUATION, QUESTIONS FOR THE PRESENTATION AND DEFENSE OF THE THESIS, SUGGESTED GRADE

Summarize your opinion on the thesis and explain your final grading. Pose questions that should be answered during the presentation and defense of the student's work.

The author implemented the required path planning algorithms and two collision detection approaches. All of these have been evaluated, even though the reasoning for selecting these particular approaches and algorithm performance evaluations has been shallow. An extension for multi-vehicle planning has been proposed and demonstrated in simple simulated scenarios. A single-UAV deployment demonstrating the ability to plan and follow a trajectory and avoid obstacles has been presented instead of the required multi-UAVs deployment demonstrating the ability of multi-UAVs path planning, the reason for which has not been elaborated.

I recommend the following questions during the thesis defense:

1. Describe which motion model of UAV is assumed for the motion planning and why it has been selected. Is this model suitable for the used experimental vehicle?
2. How do you guarantee that the replanned trajectory for the given UAV is collision-free after detecting a collision with another UAV and performing the replanning routine in the proposed multi-UAV path planning?
3. Consider a collision between two UAVs has been detected for a certain UAV in the multi-UAV planning. Then, the replanning routine is initiated. If the performance mode (as denoted in the thesis) is used, does this mode guarantee providing a feasible solution? If the found trajectory is not optimal, which modifications in the algorithm would be needed to achieve its optimality (or at least converge to optimum)?

The grade that I award for the thesis is **D - satisfactory.**

Date: **27.5.2022** Signature: