ČVUT ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

# REVIEWER‘S OPINION OF FINAL THESIS

## I. IDENTIFICATION DATA

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| **Thesis name:** | **Time Parameterization of the Manipulator Path** |
| **Author's name:** | **Krystof Teissing** |
| **Type of thesis :** | bachelor |
| **Faculty/Institute:** | Faculty of Electrical Engineering (FEE) |
| **Department:** | Cybernetics |
| **Thesis reviewer:** | Jan Kristof Behrens, M.Sc. |
| **Reviewer's department:** | CIIRC |

## II. EVALUATION OF INDIVIDUAL CRITERIA

**Assignment** **extraordinarily challenging**

*Evaluation of thesis difficulty of assignment.*

The student was sent on the hunt for a subtle but significant problem in the robot control software of a robotic work cell: the robot's motions were not smooth enough. Vibrations and low robot speeds were observed. The assignment asks to review the existing implementations of both, the motion planner as well as the time parameterizer, find suitable configurations, and adapt the algorithms as required. Emphasis was given to the time parameterization approach. The topic of robotic motion generation is an active field of research and solving this assignment in its most general interpretation would mean going beyond the state of the art.

**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.*

The student elaborates on three algorithms for time-parameterization and explains them with good clarity. On the planner side, only the MoveIt! Cartesian planner is used (presumably). This is a bit unfortunate as this planner has known bugs or shortcomings, but satisfies the assignment.

Testing the existing algorithms is done, but limited to high-level quantitative evaluations as computation time, end-effoctor deviation from nominal path and execution duration for different parameterizers and configurations. However, the jittery motions motivating this work are not evaluated quantitatively. The thesis contains plots of the motions, which aim to show the motion quality. A bit more interpretation would be great.

The student identified a problem with robot's software configuration: the kinodynamic limits were unspecified. He derived theoretically the missing values from the robot's geometry and the actuator specification. The results are also verified in experiments. This part of the thesis goes beyond the assignment.

**Method of conception** **correct**

*Assess that student has chosen correct approach or solution methods.*

The work should quantify the observed problem, to enable measuring the success of the taken steps. The second problem in the thesis is that the parameterizers were tested only on non-smooth joint-trajectories originating from the flawed MoveIt! Cartesian planner. Including a known-to-be-smooth joint-space trajectory in the experiments would have been a valuable addition. The comparison of the two alternative time-parameterization approaches (TOTG and TOPP-RA) is not fully valid, because TOTG applies a smoothing of the trajectory while TOPP-RA sticks precisely to the given path in joint-space. Applying equivalent smoothing for both algorithms would be the remedy.

The student identified most of the above problems and attributed the observations correctly to the causes. Reflecting the above comments in the thesis would be outstanding.

**Technical level** **A - excellent.**

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

The student gained and used good knowledge of the robot control software stack. The material presented shows that he can analyze complex technical systems. He also contributed adapter code to use TOPP-RA within ROS. The description seems sound, but the code was not linked in the thesis for inspection. Experiments including non-deterministic components should be conducted repeatedly with different random seeds to show the variability of the results. This is especially valid for the motion planner, as it uses a sampling-based approach. The presented results seem to be reasonable.

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

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

The thesis Is easy to read. The formulas are set well and symbols are explained. The student is a bit hesitant to make definite conclusions from the experiments (maybe because it might not fit to the thesis structure that well). A few typos and punctuation errors remained in the thesis, but are at a frequency which does not affect the readability.

**Selection of sources, citation correctness** **A - excellent.**

*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 use of citations is done well. It is clear what is the student’s contribution and what was taken from other sources. For a scientific publication, the related work section will have to be extended, but for a Bachelor’s thesis it is more than sufficient.

**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 student reached a good understanding of the problem and developed a set of tools to work on further improvements of the motion planning setup for industrial manipulators. Such improvements would possibly extend the state of the art and be worth publishing. Thus, I consider this bachelor thesis to be successful.

## III. OVERALL EVALUATION, QUESTIONS FOR DEFENSE, CLASSIFICATION SUGGESTION

*Summarize thesis aspects that swayed your final evaluation. Please present apt questions which student should answer during defense.*

The student was presented with a very challenging technical problem that is actually not solved in the literature. The assignment was fulfilled, although the results would suggest a different emphasis in the thesis. That is fine: the thesis represents a real contribution towards achieving smooth operation of robotic manipulators.

Remarks:

- The term *pose* usually refers to a point in the SE(3) manifold, i.e., a translation and a rotation. A point in the robot’s configuration space is called *configuration* or *joint-state*.
- Sec. 2.2.1: The transformation matrix T is not defined and the definition of *inverse* and *forward kinematics* computations should be more detailed. What are the properties of T? What are the properties of an executable trajectory? It is true that MoveIt! represents trajectories by a series of trajectory points (set of joint angles, velocities, accelerations, and a time). The implicit assumption is that these points can be interpolated by splines.
- Sec. 3.1: ROS implements three interprocess communication protocols: publisher-subscriber via topics (UDP), service-server based (TCP), and actions (long running preemptable activities).
- Sec. 3.2: sampling based planners are building a graph or tree in C_free to connect start and goal configurations. Nodes are configurations and edges are valid motions. Candidate configurations are SAMPLED from C and checked if they are in C_free and connectable to the graph structure.
- Sec. 4.1: The matrices from Eq. 4.1. are not transformations.
- Fig. 5.5: It is not clear how epsilon_max is chosen

- Sec. 7.2: Why are only cartesian paths tested (I wrote above about it)?
- Sec.7.3: Orientation error of eef is neglected.
- OMPL has more planners than just the Cartesian path planner.
- Sec>7.6.3: Why is the TOTG path error bigger for the circle path? Explanation missing.
- Table 7.8: It seems weird that the execution for both algorithms takes ~0.2 s longer than planned. Is there maybe some communication time in the measurement?
- Fig.7.10: How are the accelerations obtained? The joint states topic contains positions, velocities, and efforts.
- Chapter 8: This thesis did not describe the theory of path planning. It was time- parameterization of trajectories.

**Questions**:

1) Would the Cartesian planner and the IPTP be better suited for 6 DoF robots? Can the observed problems be connected to the redundancy of the KUKA iiwa robot?
2) How could one generate a smooth joint-space trajectory for testing the time-parameterization approaches?
3) How is the deviation of the end-effector connected to a deviation in joint-space? How can the deviation introduced by the smoothing in TOTG be quantified in the task space?

I evaluate handed thesis with classification grade **A - excellent.**

Date: **1.6.2021** Signature: