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Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Evgeny Tsykunov

PhD Program: Engineering Systems

Title of Thesis: Human-swarm interaction for the guidance and deployment of drones using impedance control and tactile feedback

Supervisor: Associate Professor Dzmitry Tsetserukou

Name of the Reviewer: Kamal Youcef-Toumi

I confirm the absence of any conflict of interest.	**Signature:** Kamal Youcef-Toumi **Date: 18/01/2021**

The purpose of this report is to obtain an independent review from the members of PhD defense Jury before the thesis defense. The members of PhD defense Jury are asked to submit signed copy of the report at least 30 days prior the thesis defense. The Reviewers are asked to bring a copy of the completed report to the thesis defense and to discuss the contents of each report with each other before the thesis defense.

If the reviewers have any queries about the thesis which they wish to raise in advance, please contact the Chair of the Jury.

Reviewer's Report

Reviewers report should contain the following items:

- Brief evaluation of the thesis quality and overall structure of the dissertation.
- The relevance of the topic of dissertation work to its actual content
- The relevance of the methods used in the dissertation
- The scientific significance of the results obtained and their compliance with the international level and current state of the art
- The relevance of the obtained results to applications (if applicable)
- The quality of publications

The summary of issues to be addressed before/during the thesis defense

- I believe that the thesis is of good quality. I raised some questions and made some suggestions to improve the thesis. The author has already responded to all of them.
- The topic of the dissertation is relevant. We see an increase use of drones, and autonomous agents in general. This use in many and diverse applications. They include photos/videos for (i) surveillance, inspection, and insurance (ii) agriculture (monitor crops and collect soil data), and (iii) delivery.
- The thesis considers methods for guidance and deployment of drones using human-swarm interaction, impedance and tactile feedback control. The thesis also considers unstructured environments. The work proposes vibrotactile feedback for both guidance and deployment of the swarm of small-scale quadrotors.
- I found the thesis work novel, especially the development, use and implementation of impedance and tactile feedback control in the human-swarm interaction for the guidance and deployment of drones. The video demonstrations are really cool!
- The results of this work have scientific significance. In addition, they have been published in peered reviewed journals and conference papers.

The comments/questions were conveyed to Skoltech on January 3rd and were addressed by the author.

- The videos are cool!
- The abstract needs reorganizing and improving. I suggest you first state the problem, why it is a real problem, its societal impact, corresponding challenges, and technical gaps. Then the approach and proposed solution followed by the thesis contributions.
- Check spelling
- The writing needs improvement. You can start each paragraph with a leading sentence that summarizes the message. The paragraph then provides details to support the message of the leading sentence. It is important to have the paragraph stay with the message of the leading sentence. This will make your ideas organized and clear.
- ..
- Figure 2-7 shows velocity and impedance on the vertical axis with time on the real axis but there seems to be only one trace in dotted line. The units associated with the impedance needs to be corrected.
- The text on page 45 says " … shown in Figure 2-11." Without any explanation to what the reader is supposed to see in the figure. It is important to explain to the readers what they are seeing in every figure, table, picture etc…
- How are tactile cues used when the number of drones is large?
- Add a paragraph at the end of each chapter summarizing the findings of the chapter.
- The intermediate reference frame C is not shown in Figure 4-1 nor defined, as this relates to Equ. (4.1).
- Equ.(4.5) needs clarification regarding the direction of force Fi and the axis about which the moment Mi is applied.
- It should be stated that the net force $F=u_1$ in Equ.(4.7) is in the direction of the body axis Z_B.
- The same applies for the moments in Euler's equations.
- Fix the subscripts in (4.11)
- Why is r assumed small in (4.11)?
- Equ.(4.13) is missing "dt" in the integral action term.
- Mismatched parentheses in (4.14).
- Section 4.1.3, are there issues with the use of high derivatives? Are these in the measured or the command signals?
- Equ.(4.16) represents positions. Does orientation play a role in some applications?
- In the text associated with Figure 4.2 and elsewhere in the thesis, impedance should be Force/velocity.

- On page 61, define F_{ext}. A schematic of the hand, the primary quadrotor and associated forces and velocities would help in understanding the concept and the notation.
- Page 62, what is "impedance link"?
- Equation (4.19) on page 62 is, technically, not in state space form. All differential equations should be 1st order equations. You need to introduce 2 state variables, say position x(t) and velocity v(t).
- Starting with equation (4.22), use proper notation to differentiate between the time and frequency domains.
- Is u in equ.(4.28) the actuator trust ? also, usually the drag coefficient is unitless. Perhaps you need to explain c_d
- What is the PID controller on page 65 for? Is it for the simplified model of Figure 4-3?
- The text on page 65 and 66 do not show how the hand trajectory goes in the controller, especially Figure 4.5.
- Correct units of impedance in Figure 4-6.
- Explain what the reader is supposed to see in Figures 4-6 and 4-7.
- Page 68, it is not clear how the response was obtained for the 'without impedance' case. It would be better to show how the trajectories and the control inputs were generated.
- What is the difference the impedance control of Figure 4-8a and a conventional filter, say a second order, that takes the hand motion as an input and generates an input for the drone? This is what is often done in robot control, the command is filtered by a 2nd order system before it is sent to the actuator drivers. Also, there isn't a clear connection between equ.(4.29) and Figure 4-8a. Finally, how does one deal with the possible change in configuration as the quadrotors fly?
- Page 69, the text does not explain how the operator pulls or pushes on the virtual mass. Is the operator supposed to feel the interaction with the virtual mass?
- Page 71, explain in the text the order R^{n2} in G and Imp.
- Make sure the dimensions in all terms work out in Equ.(4.34) along with the functions f_1, f_2 and f_3, their arguments and their contribution/role to the overall signal.
- The "quadrotor physical world" of Figure 4-10 contains actuators and sensors. The Figure though implies otherwise. Also, given that the sensors in the yellow bubble include the vicon motion capture system, what do the actuators in the red bubble represent?
- What does dynamic stability mean on page 77? What are you referring to?
- What does Figure 4-17 tell us?
- Are the obstacle locations known or detected/identified automatically in section 4.4?
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- What are the contributions of the new tactile display prototype, device with eccentric rotating mass (ERM)?
- Why is Figure 5-2a is labelled "contracted state" for the case with increasing distance? Contract means a decrease in size! Is it to decrease the size of the configuration?
- What happens when the drones end up moving in different directions?
- It is not clear from the text where the input to the ERMs come from?
- What is the effect of sustained vibrations on the operator?
- Why is the recognition rate about 77%? What limits it?
- What are the implications of the long response times in Table 5.2?
- What are the issues associated with a larger number of drones?
- I suggest you add additional description on the flow of information and interaction between the hand and the drones, etc..
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- Figure 6-1 does not show that there is an impedance control between the drones as was indicated in earlier chapter.

- How to reduce the differences (right most column) in Table 6.1?
- The maze trajectories using tactile are more random with much more time than the visual ones in Figure 6-7!
- The text does not provide enough information about how the tactile/impedance etc. control were implemented in chapter 6.
- There is no apparent discussion of the dynamic behavior between drones, especially the proposed impedance control.
- How does the human operator keep up with rapid changes in the drone configuration while performing the control?
- Did the subjects comment on the effectiveness of the tactile approach versus the visual especially while controlling the drones through obstacles?
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- .
- It seems that the results show that the visual approach generally provides better performance. I would assume that this will be the case for the large-scale case. So it is important to state when the tactile approach is applicable or preferred.
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Provisional Recommendation

☐ *I recommend that the candidate should defend the thesis by means of a formal thesis defense*

☐ *I recommend that the candidate should defend the thesis by means of a formal thesis defense only after appropriate changes would be introduced in candidate's thesis according to the recommendations of the present report*

☐ *The thesis is not acceptable and I recommend that the candidate be exempt from the formal thesis defense*