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Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Yuri Sarkisov

PhD Program: Engineering Systems

Title of Thesis: Design, modeling, and control of cable-suspended aerial manipulator

Supervisor: Associate Professor Dzmitry Tsetserukou, Skoltech

Co-advisors: Dr. Konstantin Kondak, DLR; Dr. Christian Ott, DLR

Name of the Reviewer: Jacques Gangloff

I confirm the absence of any conflict of interest (Alternatively, Reviewer can formulate a possible conflict)	**Date: 14-01-2022**

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

This report is about the PhD dissertation written by Mr. Yuri Sarkisov aimed at obtaining the PhD Degree delivered by the *Skolkovo Institute of Science and Technology* in the doctoral program *Engineering Systems*. This thesis has been prepared at DLR Institute of Robotics and Mechatronics (Wessling) and Skolkovo Institute of Science and Technology (Moscow) under the supervision of Dzmitry Tsetserukou and co-supervision of Konstantin Kondak and Christian Ott. The research work was conducted within the H2020 AEROARMS project, which aims at developing aerial manipulation technologies for industrial inspection and maintenance.

The dissertation written in English is organized in 8 chapters including the introduction and conclusion and 4 appendices for a total of 204 pages. The bibliography lists 208 references. The length and density of the dissertation is completely justified by the density of the work.

This thesis is about a new type of aerial manipulator, suspended under a carrier by a cable. The cable-Suspended Aerial Manipulator (SAM) platform used in this work has been developed by researchers from German Aerospace Center (DLR) Robotics and Mechatronics Center (RMC) within the H2020 AEROARMS project. It is suspended from a mobile crane and equipped with dual actuation: winches and omnidirectional propeller-based actuation. This new concept allows for increasing payload, dexterity, accuracy and dynamics while reducing power consumption, noise and total weight of the system. This is currently a pretty active research topic with many challenges that still need to be tackled. This work focuses mainly on the control of such a system and addresses two intrinsic problems of such a structure: oscillation damping and actuation redundancy handling. Oscillation rejection is a generic issue when dealing with robots involving cables. In this case, the main vibration modes are due to the oscillation of a double pendulum constituted by the carrier main cable+hook and 3 rigging cables connecting the hook to the aerial platform. The length of these rigging cables is actuated by 3 motorized winches. This rigging system is a very interesting feature that makes SAM really unique, since it allows for generating constant moments on the platform at the cost of minimal energy consumption. It adds obviously redundant actuation to the system since the 8 propellers mounted on the platform are able to generate a 6-DOF wrench, at the cost of a lower efficiency but with higher dynamics. This redundancy is used in this work to maintain the platform horizontal during the motion of the suspended robotic arm with a Hierarchical impedance-based Whole-Body Controller (HWBC). The proposed control laws have been validated with simulations and various experiments. Lots of experiments were carried out during this thesis in various contexts: from the easier indoor laboratory context to the most challenging outdoor industrial context. Experiments quality and quantity are outstanding, considering the complexity of the system.

The dissertation is written in a clear and pedagogical manner. All symbols are well defined and consistent in the whole document. Theoretical developments are sound with the assumptions clearly reminded. Simulations and experiments are relevant and their conditions are clearly defined.

Chapter 1 is dedicated to the state of the art of the domain which starts by reminding where aerial robotics is located within the general robotics taxonomy. The main works related to this project are cited, accurately described and compared. It ends by stating the main research goal of the thesis (how to enhance manipulation performance and operational safety for the aerial manipulation in industrial applications) and by listing the expected contributions:

- Synthetizing and characterizing a robust control law that efficiently rejects transient disturbances on the aerial platform
- Synthesizing and characterizing a robust control law exploiting actuation redundancy that optimize manipulation performance while rejecting constant disturbances

- Extensive experimental assessment in an industrial environment.

These are indeed the contributions of this work. The two theoretical contributions could be, to some extent generalized to other types of robots, like cable driven parallel robots (CDPR). The experimental assessments simulate very accurately realistic industrial scenarios.

Chapter 2 reminds the general theoretical tools and concepts used in the manuscript. This makes the dissertation self-contained and thus very useful and understandable for a non-specialist.

Chapter 3 describes SAM in detail. The optimized propeller configuration is presented and explained. The planar disposition of the propellers is very interesting here since it minimizes collision risks with the cables and with the robotic arm. The propulsion units are modeled and identified. The ESC driving the motor does not regulate the velocity of the rotor, so the relationship between the PWM control signal and the angular velocity has been identified on a test bench. Note that from our experiment, regulating this velocity accurately yields a great improvement in the quality of the global wrench control loop. This regulation not only compensates for voltage variation of the power supply but also compensates for variations in motor characteristics and especially the back-electromotive force (EMF) coefficient. The performance of the control schemes tested in this work (which is already good) could significantly benefit from this simple modification. In section 3.3.1.4 dedicated to the propulsion unit identification, it is noted that the ESC has a dead zone which is attributed to frictions. IMHO this dead zone is here inherent to the use of ESCs without rotor position feedback and has little to do with friction. This kind of ESC relies on back EMF to estimate the position of the rotor and a minimal angular velocity is required to measure this back EMF. With a position feedback sensor like a hall sensor, this dead zone can be avoided. A frequency analysis has also been carried out in this chapter assessing the influence of propeller rotation on IMU noise. This is indeed an important issue with propeller actuated aerial robots mainly due to the rotor and propeller imbalance. The analysis in section 3.3.1.6 is restricted to one specific angular velocity. It could be extended to a range of velocity and adaptive notch filtering could be implemented to reject specifically the spike due to rotor imbalance.

Chapter 4 is dedicated to the platform active oscillation damping using only propeller actuation. Indeed, the winch actuators have a more restricted bandwidth and would not be able to efficiently reject wrench disturbances on the platform. Since the control should rely only on embedded sensors, it is not possible to measure the angle of the carrier cable. Thus, since the oscillation mode of this link has a low frequency, it is possible to estimate this component by filtering out the high frequency mode from the platform gyro sensor data. I found this approach interesting and relevant in this case. Simulations show that the phase introduced by the first-order filter does not penalize significantly the rejection performance. The tuning method is very interesting. Instead of tuning the damping gains, the problem has been reformulated in an optimization of a standard cost function, trade-off between accuracy and control signal energy. It is not clear to me how the value of σ was selected. Since this new tuning parameter affects the energy of the control input, maybe the actuation saturation should be taken into account to tune it in a way the control signal stays within admissible values ? In figure 4.9, equivalent control torque is given for the two joints of the double pendulum. One torque goes over 1000 Nm which seems important. I'm wondering if the SAM is physically able to generate such equivalent torque.

Chapter 5 deals with a hierarchical whole-body control with the winch-based actuation and kinematically redundant manipulator. The goal here is to reject static disturbances mainly due to the motion of the carried robotic arm, using the three actuated winches. This is carried out by a secondary task that keeps the model center of mass always under the suspension point, thus neutralizing the torque due to gravity.

While the main task of this control scheme is to control the Cartesian pose of the robotic arm end effector accurately. I read this part with great interest, partly driven by my interest in cable-driven parallel robotics. The three rigging cables may be considered as a pretty atypical CDPR. I think that in some situations some cables may become slack, especially when the robotic arm is fully horizontally stretched and is carrying its full payload. I was wondering if this situation may happen during normal operations. It may also happen dynamically if the arm is accelerating too fast around a horizontal axis. In figure 5.8, simulations show a maximum control force of -4000N on z which is huge. I was wondering if these values are realistic.

Chapters 6 and 7 are dedicated to experiments. Chapter 6 is focused on the experimental validation of the proposed control laws in various situations while chapter 7 is more focused on real-life industrial scenarios. These two chapters are of great value since they probably required a lot of work. I measure the difficulty of making all these assessments, sometimes involving heavy equipment, with all the complications linked to safety with such a powerful device. The candidate and the team that helped him should be praised for this impressing achievement. The results validate the benefits of the proposed control laws clearly. As pointed out by the various robustness tests, they should be pretty robust to parameter variation and uncertainties, which is important in an industrial context.

To conclude, I consider that overall, both the quality and quantity of the results presented in the thesis manuscript are all of excellent level. The associated publications are in the best conferences and journals of the domain. So I definitely recommend the defense of this thesis by the PhD candidate.

☒ *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*