Thesis Changes Log

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-supervisor: Dr.-Ing. habil. Konstantin Kondak (DLR)
Co-supervisor: Dr.-Ing. Christian Ott (DLR)

The thesis document includes the following changes in answer to the external review process.

I sincerely appreciate constructive feedback, comments, and recommendations to my PhD Thesis provided by Reviewers. Thank you very much for your time and efforts. Provided feedback helped me to improve many aspects of my work including delivery, reasoning, and readability. Moreover, it showed great possibilities for further research investigation and analysis. Although I tried to address each point at my best, some of the comments might take deeper perception and might be considered as the future prospects of my research.

Below I provide the Thesis Changes Log. The comments from reviewers are numbered and in bold font. Responses are given in plain font after each comment.

Professor Clement Fortin (Skoltech, chair)

Thank you very much for the proofreading of the entire thesis. Your positive feedback gives me the feeling that I managed to shape my research work according to the best practices of the design research methodology. All comments concerning the grammar in the annotated document were taken into account.

Associate Professor Alessandro Golkar (Skoltech)

Thank you very much for the positive feedback on my work! I would like to address here two points that you noted before your final review.

1. **To reconcile the Section 1.2 “Literature review” with Chapter 2 “Fundamentals.”**

I decided to keep them separate. The former is devoted to the state of the art, while the latter is used to present theoretical tools that are used through the thesis in order to make it self-contained. The structure was inspired by the thesis “Whole-Body Impedance Control of Wheeled Humanoid Robots” by Dr. Alexander Markus Dietrich (TUM) (https://elib.dlr.de/99414/1/dietrich2015c.pdf).

2. **As the work relates to the contributions of a team of researchers, it is of paramount importance that the author clearly specifies what are the individual contributions provided to the work.**

I modified the thesis a bit in order to highlight the personal contribution. In cases, when the contribution was made by the team corresponding acknowledgments were provided.

Professor Jacques Gangloff (Strasbourg University)

Thank you for the positive feedback and your valuable insights on the propeller-based actuation and cable-driven robots! I really reevaluated some aspects of my thesis from a different perspective.

3. **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.**

Indeed, the speed control-loop at the actuation level should increase the performance of the control loop at the system level. This feature is specified as a future work.

4. **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.**

Indeed, the friction is negligible here, the main reason is in the sensing of the rotor position. I totally agree with you. I modified the subsection “3.3.1.4 Identification” accordingly:

“

As it can be seen, at the low PWM commands, the behavior is different from linear (outliers in Figure 3-13a), so we defined two complementary regions in addition to the operational one. The first one is the dead zone (blue piece) at which the motor does not spin at all (blue line) due to zero back electromotive force (BEMF), and the second one is the nonlinear piece (yellow line) at which the motor starts to spin with low BEMF, i.e., a transition between dead zone and operational range (green piece), see Figure 3-13b. During this transition, the minimum angular speed is generated in order to measure BEMF required for the rotor position estimation [Damodharan and Vasudevan, 2010]. As soon as the measurement of BEMF is reliable (when angular velocity exceeds a certain low threshold), the characteristic behaves linearly.

”

5. **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.**

Yes, I totally agree. This analysis might be extended. I do not have an access to the testbench anymore, so I extended subsection “3.3.1.6 Frequency analysis” with the following reasoning:

“

It can be seen that when the motors are activated, the high-frequency noise with a frequency of 39.2 Hz appears. Since a periodic sources (8 rotor groups) produce the noise containing dominant harmonic component, the higher rotor group’s rpm the higher noise frequency. Thus, vibrations induced by rotor groups in a range higher than in the considered experiment would have even higher frequency (it is worth mentioning that intensity might vary). In general, adaptive notch filtering could be applied to reject noise spikes in the IMU measurement for the commanded rpm.
”

6. **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 ?**

Basically, there was no specific strategy presented in the thesis that might help to select the “correct” sigma σ. I kept this point open as the designer choice depending on the specific mission requirements.

In order to provide a better intuition about possibilities to the reader, based on your wise suggestion I extended “4.3.5 Gain tuning rule” subsection with the following.

“

Depending on the designer’s choice (balance between oscillation damping and power consumption), we can select one proper combination of gains. It might be useful to consider the rotor group saturation at the specific system as one of the criteria for the selection so we do not command too high wrench. Another beneficial criterion might be the proximity of the obstacles in the environment.
….
The deep investigation on strategies for the σ selection is beyond the scope of this thesis.
”

in “4.3.6 Simulation studies” I specified the following reasoning:

“

In the scope of the simulation, the σ was selected to provide high control gains, and, consequently, to decrease convergence time.
”

and in 6.4 section devoted to the experimental investigation of the controller, I referred to the simulation studies (we had reachable wrench by rotor groups with selected sigma).

7. **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.**

In general, I tried to keep the controller chapters as independent as possible from the specific platform (the SAM, in my case) that is why I have not analyzed the reachability of high joint torques (since it depends on actuation power).

Nevertheless, I agree that it is important to provide some sense of reality for the reader. Since this torque is in the joint space, it is highly dependable on the geometry of the double pendulum (namely, Jacobian values). I conducted a simulation for the typical values that we used in the system (namely, the length of the crane's chain equals 6 meters), and it showed that 1000 Nm is possible (on the joint level). I also extended 4.3.6.1 subsection with calculation results:

"

Let us calculate the required planar wrench corresponding to the resulted maximum torques. As can be seen in Figure 4-9 and Figure 4-10, at t = 0.285 s the tau1 = 1172.62 Nm, tau2 = 332.42 Nm, and q2 = 4.62 degrees. The planar wrench can be expressed from (2.4) after calculating the Jacobian matrix (4.9) as w_b = [140.48 N , 23.35 Nm]. As we can see in Figure 3-14, the calculated wrench is reachable by the SAM platform presented in chapter 3.

"

8. **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.**

I can report that we have not experienced the slacking during the normal operation (even with the jerky motion of the robotic arm). Nevertheless, it is important point to address. Since the dynamic case of the slack depends on the robotic arm dynamics which depends on the specific robotic arm and in general might be slowed down by the control command, I analyzed the static case only.

I defined the static slacking condition as the case when the resulted COM (platform and robotic arm) is located beyond the circle (in the plane of the platform) which is plotted through three points corresponding to the winch cable "attachment" to the platform. The analysis has shown that even with harsh conditions (due to heavy platform) slack is hardly possible (we have to exceed the maximum payload for the selected robotic arm (KUKA LWR IV) to make it possible) extended the subsection "3.3.5 Mechanical structure" with the following:

"

It is worth noting that with given weight-geometric characteristics even for fully horizontally stretched robotic arm with maximum payload at the end effector, in the quasi-static condition, the COM of the SAM will be located below the mechanical frame border. Moreover, it will be mostly inside of triangle W1W2W3, see Figure 3- 21. Thus, the slacking of the rigging cables in normal and close to the extreme (but possible) conditions is unattainable for the considered system.

"

9. **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.**

Thank you for pointing it out. Indeed, the values are not realistic, they correspond to the case of high control gains which were selected arbitrarily to speed up the convergence process. I reconducted the simulation with gains from a real setup (so they make more sense now) and updated figures. Roughly, P gain in the old-simulation was 10 times higher and D gain 3 times higher than in the real setup.

Assistant Professor Gonzalo Ferrer (Skoltech)

Thank you for the very positive feedback on my research!

10. **My only comment, and this is not a concern, is that the term aerial is not accurate to the SAM idea and I got the wrong impression of a flying platform supporting the SAM. It is a great motivation, but in practice the system in the real world has been validated in crane-based platforms, and given the dimension of the system, it looks a more convenient platform to use.**

As you mentioned, the big team worked on the experimental setup development, so it was not my pure decision to name it the SAM (although I liked this version among others). However, I would like to provide some historical remarks regarding the SAM. Initially, the helicopter was assumed as the main carrier. So, originally the system was trully “aerial” (in my humble opinion, even with a crane the SAM is still “aerial” but not “flying”). At that time, the crane was just a handful tool for the validation (as more cheap and accessible setup). Through experimental investingations and dialogue with industry, the team came up with a conclusion that the crane actually is much more practical for real-life applications.

Professor Dongjun Lee (Seoul National University)

Thank you very much for the positive feedback on my thesis! Your comments strongly supported me in a better explanation of what, why, and how has been done.

11. **It appears that the rotors are unidirectional. Further, the winch actuation is also unidirectional (only via tension). What would be the implication or limitations imposed by these constraints on the actuations?**

The implication of the unidirectionality can be considered as the ability to control only positive (or only negative) values along one axis: for rotors – we can generate only positive thrust, for winches – only positive tension.

Indeed, the unidirectionality of both actuators implied specific limitation. We can write down: $w = A*t$ (where w is a wrench vector, t is a vector of generated forces (either thrusts of tensions) and A is the allocation matrix). In general, Moore–Penrose Pseudoinverse might be applied to calculate the generated force vector t for the desired wrench w, but there is a risk of getting negative values of tension or thrust that is not feasible for our task. For the props, A would have dimension 6x8, while for the winches 6x3 (with the last line of zero since winches cannot affect the yaw rotation).

Taking into account the aforementioned introduction, for the fixed props, the omnidirectional wrench can be generated by only positive thrusts (since there is no reverse mode; If there would be reverse we would lose some performance in the opposite directions due to worse propeller aerodynamic characteristics, e.g., angle of attack), so min 7 actuators are required (it was shown in [Tognon and Franchi 2018]). This restriction implied the following: the extra control term in (3.2) Mapper 1 is required in order to provide always positive thrust values (feasible control inputs that produce the desired wrench). However, this extra term should not produce any effect on the wrench.

In the case of the winches, the actuation is also unidirectional: cables can pull, but not push. It is worth noting that we have under constrained system, i.e., the aerial platform has 6 degrees of freedom and it has only 3 cables to control. So, there is no null-space at which we can set additional control effort (as we did with rotors). Therefore, the allocation matrix would not provide any solution, i.e., tensions will not be able to generate all desired wrenches at the platform It would lead to the limitation in a workspace. To this end, in order to work only with wrench feasible pose, we restricted our control task in HWBC controller to the case with COM location at zero, so the desired wrench would be reachable: [0; 0; mg; 0; 0; 0]. Since we have position-controlled actuators, we used inverse kinematics for control.

I extended “3.3.4.4. Quantitative requirements” subchapter in the winch design section with the following paragraph to stress the reader’s attention on the positive tension requirement:

“

Additionally, it is worth noting that each winch actuator is also unidirectional (in terms of tension): cables can be pulled but not pushed. Since we have an under constrained system, i.e., the SAM platform has 6 DOF and only 3 cables, there is no null-space at which we can set additional control effort as we did in (3.2). So, the corresponding allocation matrix relating the positive tension forces and corresponding generated wrench will not provide arbitrary solution [Borgstrom et al., 2009]. This restriction leads to the limitation in the workspace that has to be kept in mind during the control strategy selection.

“

12. **How much actuation is shared between the winch and rotor actuations?**

There is indeed an actuation redundancy in the system. The rotor actuation can affect all 6 DOFs of the platform, while the winch actuation might affect only 5 DOFs of the platform (all except yaw).

However, there is no direct sharing since actuation efforts applied to the different DOFs of the system dynamics. Intuitively, the system might be modeled either as a free rigid body with holonomic constraint (chain of the crane and winch cabling) and attached robotic arm or as a double pendulum with passive joints and reconfigurable second pendulum link (due to winch cabling evolution and robotic arm motion). Current control strategies rely on the latter interpretation. Namely, the rotor actuation affects the damping terms of the double pendulum dynamics while the winch actuation affects the translational DOFs of the platform to counterbalance robotic arm motion. It is worth noting that the winch actuation has a more narrow bandwidth, therefore the rotor groups are used only to counteract the disturbances induced on the platform.

13. **If the winch actuation can counter-act gravity of the SAM, wouldn't it be a simpler solution to attach the KUKA arm directly on the (actuated and dexterous-to-certain-extent) booms (with no cables)?**

Such a concept (robotic arm at the crane's boom) was also considered as possible. However, there are three significant drawbacks that directed us toward another path.

First of all, the crane boom has a tendency to noticeably shake even after applying the non-strong perturbations (e.g., wind), especially in the extended configuration (when the crane has a long leverage with respect to its base). So, the wrench generated by the robotic arm motion would force the crane to vibrate (it might be considered as a robotic arm installed at the flexible beam). Thus, it would require additional actuation installed directly on the crane that would directly dampen the whole structure. Modification of the crane is not really practical, so we decided to proceed with a solution that can be utilized as a payload with any crane (like plug and play).

Secondly, the crane boom precision control is hardly possible (from my experience) while it is manually controlled by a human-operator (most of the cranes).

Finally, the workspace of such a concept is restricted by the crane structure. We believe that most of the potential elevated objects for inspection can be reached from the top (pipelines, roofs, bridges) so carrying the SAM by the chain the length of which can be altered would make more sense for such applications.

14. **Is the SAM also capable of generating a side-way manipulation operation (e.g., taking something from a narrow hole or window)?**

Yes. The SAM platform makes it possible to manipulate side-way as long as manipulation task is located in the feasible workspace. For example, the case when the SAM closes a drawer while the perturbations are damped might be found in "Compliance control of a cable-suspended aerial manipulator using hierarchical control framework" by Chiara Gabellieri et al. (IROS 2020).

Regarding the feasible workspace, since we can generate omnidirectional wrench by rotor groups we can exert a horizontal force which would move the platform in a horizontal plane similar to pushing the pendulum bob horizontally (so the height would be changed slightly as well). Since we want to avoid a long term load on the rotor group, the future work description includes the dual manipulation. With two arms, we would be able to push the platform toward desired operational spot (e.g., a window) by use of the rotor group and grasped some fixed handler (e.g., a window frame) by one arm while manipulating by the second one.

15. **It appears that the condition for the cable vibration suppression control is rather favorable (e.g., actuator-sensing collocated?) and it would be nicer to make it more explicit what is a novel and significant challenge of this vibration control (other than using just one IMU).**

Indeed, we have actuation-sensing collocation onboard, i.e., sensor (IMU) is placed (almost) at the same location as an input wrench (generated by rotor group). However, the nature of the system vibrations is more complex than we can sense by on-board measurements. Namely, vibration of the system contains a sum of all vibration modes (each of which vibrate at its own frequency). There are two masses (crane's hook and the platform), so vibration to dampen contains two modes. At the same time, we can sense neither both vibration nodes separately nor the system full state. Thus, the main challenges might be specified as:

- to dampen the system without access to the system full state: estimation of the low frequency component (corresponding to the crane's hook motion) by filtering out the high frequency mode from the on-board platform gyro sensor data

- to utilize an approach that is model-free and robust to disturbances and uncertainties (which was field-validated)

- to tune task with "sense": tuning is formulated as an optimization problem (instead of direct damping gains tuning) to select trade-off between performance and energy consumption (this aspect was not investigated in the thesis though but it opens opportunities for switching gains depending on the operational scenario)

In order to better highlight the aforementioned challenges I slightly modified the "4.1 Problem statement" section in the Chapter 4 devoted to the oscillation damping controller.

16. **It would be a bit better if empirical justification is also provided on the 2 rigid-link modeling of the cable.**

In section "4.3.6 Simulation studies", the crane chain is modeled as the rigid link with zero mass and inertia (this assumption is mentioned in 4.2.1). Adding a certain mass and inertia to the cable (crane's chain) would not change controller structure, but would change slightly the optimal controller gain values. Since the density of the crane chain is crane-dependent and total crane chain mass is length dependent, we neglected its inertial parameters in order to keep controller independent on the system model.

In fact, the crane chain might be modeled as elastic density with its own natural frequency which is higher than vibration modes we dampen. In case if you are interested, you might find elastic modeling and identification of the SAM in MS Thesis by Michael Rothammer: "Modeling, Observing and Controlling a Cable-Suspended Aerial Manipulator as a Constrained System", available online: https://elib.dlr.de/148625/. In conclusion, Michael noted that the rigid pendulum is an adequate model to represent the SAM.

17. **How also did you set the inertial of these cable segments, which I guess would be fairly small? Doesn't it cause any problem of singular inertia metric or could you just eliminate them during the process of dynamics reduction?**

During the bringing of the platform to the operational spot by the crane, the robotic arm configuration is fixed and the rigging cable lengths are fixed. So, the second link of the pendulum has fixed inertia and mass. To this end, we neglected the dynamics of the rigging cables in the design of the oscillation damping controller.

At the same time, for the winch-based control, we neglected the inertial properties of the rigging cables (winch-controlled cables) since their masses are fairly small (around 40-50 grams per cable, stainless steel 316, diameter 3 mm). I modified “5.2.1 Modeling assumptions” to clarify this point. Therefore, each cable segment was considered as a massless kinematic (with integrated translational DOF) constraint which we eliminated in the dynamic reduction process (“5.2.2 Dynamic formulation” for more details) such that the resulted inertia tensor is positive-definite.

18. **The importance of frequency separation for the feedback control is well-known and it might be better to mention this to contextuate the presented framework to this concept. It would also be more convincing if some empirical data is given for this frequency separation along with the explanation on how to choose the LPF coefficients (given the signal frequency spectrum).**

Indeed, the frequency separation technique is important for the feedback control, especially for the noise filtering applications and nested feedback loops.

The “Chapter 4: Oscillation damping control with the propeller-based actuation” is devoted to the fundamental derivation of the controller. As a LPF the first-order model was used.

Explanation on how to choose the LPF coefficient (time constant of the first-order LPF) is described in Section 4.3.3: the cut-off frequency of the LPF is selected in the middle between slow and high frequency modes of double pendulum, see formula (4.13).

The sections “4.3.3 Controller derivation” and “4.3.5 Gain tuning rule” were updated with:

- frequency separation references,
- filter details,
- frequency spectrum for the simulation (empirical data for simulation, Fig. 4.6)

I would like to note that empirical data for experimental setup can be found in “Chapter 6 Experimental investigation of the proposed control strategies.” In particular, Figure 6-4 presents the frequency spectrum for the indoor setup and Figure 6-7 shows the spectrum for the outdoor setup for different crane chain lengths.

19. **Stability is claimed by using the argument of passivity, which however can be compromised by the phase-lag of LPF, and it would be nicer if some explanation or justification is provided on the adequacy of this passivity argument with the LPF.**

Indeed, phase-lag introduced by LPF might induce the instability to the system. The research devoted to the passivity of the non-linear systems with time delay is quite complex. To this end, numerical validation of the stability was additionally conducted. The section “4.3.4 Stability analysis” is updated with the following paragraph:

“

As shown, the spherical double pendulum system with artificially injected damping in joints is asymptotically stable. This statement is true for the general case. However, the phase-lag introduced by LPF might compromise the passivity and induce the instability to the system with a feedback. In order to validate that introduced time delay does not penalize strongly the

damping performance, additionally, we have numerically investigated the stability of our controller in a simulator.
"

Results of the simulation are presented after the last sentence of the aforementioned paragraph in the thesis.

20. **Stability of LQR is typically coming from their controllability or observability of the output mapping, and it is not so clear if this LQR solution should possess always the same structure as the passivity-based damping control. What are the stability criteria of ofLQR and how are they related to the passivity-based stability argument?**

Indeed, there are certain requirements for the common LQR including controllability of the system in order to have a unique solution P for algebraic Riccati equation. The theory behind output feedback LQR (ofLQR) is a bit more complex and rely on linear matrix inequalities (LMI).

- The controller guarantees the robust closed-loop stability (quadratic stability) and minimizes the quadratic cost function J subject to the system uncertain dynamics
- System dynamics is uncertain in sense that matrix A contains fixed parameters and is close to the real system but does not exactly represent it
- Stability criteria for the ofLQR are:
    - the system is output feedback stabilizable if: *The pair (A, B) is stabilizable (*there exist a real matrix K such that *(A – BK)* is stable), the pair *(A, C)* is detectable (there exist a real matrix L such that *(A – LC)* is stable), and there exist matrix of control gains F that satisfies a set of LMI. The SAM linearized model is stabilizable.
    - the system is static output feedback stabilizable with guaranteed cost if: the system is output feedback stabilizable and there exist *Q>0, R>0, P>0* and matrix *F* satisfying the set of LMI.
    - the system is static output feedback controllable with guaranteed cost if: the system is static output feedback stabilizable with guaranteed cost and it is controllable (it is controllable for out case as well).
- ofLQR allows to have a structured controller (static output-feedback gain matrix). The controller structure is defined by user. In our case, we want to dampen vibrations, so our controller should be purely proportional to the velocity.
- During the iterative controller optimization, at each step eigen values of the closed loop system with resulted F gain matrix are checked to be in the stable domain.

I updated the section "4.3.5 Gain tuning rule" in multiple places: main modification ideas are summarized above.

It is worth noting that we have shown in the section "4.3.4 Stability analysis" that the system is stable regardless of the controller gains, so by using ofLQR we seek for the optimal gains in some sense. The gains will be optimal only in the close proximity to the operational (equilibrium) point (at which the system is linearized), but they will not drive the system to unstable state out of this area, i.e., with these gains system should be stable globally.

The controller guarantees the quadratic stability, which is defined directly in terms of LMI. It implies stability in R for uncertainties *p* in *R* of the state matrix *A(p)* (stability does not imply quadratic stability though), such that there is a *P>0* for the Lyapunov inequality. It makes the system stable for any possible uncertainty for LTI (it can be seen through eigen values). More details about the connection of quadratic stability with H-infinite control, passivity theory, and stability could be found in (Amato, 2006).

21. **The symbols of body-frame angular velocity and wrench look rather similar and it might be better to use different symbol for the wrench.**

I decided to keep the notation as it is since it is well familiar in robotics community: lowercase omega for the angular velocity “ω”, and double-u “w” for the wrench.