Time delay algorithms for control of a quadcopter with suspended load

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Recently, a great deal of attention has been paid to control of unmanned aerial vehicles (UAV), such as quadcopters, multi-copters, etc. Thanks to advanced instrumentation including prompt-action and high-power actuators in the propeller control systems, and thanks to application of advanced control theory tools, an outstanding manoeuvrability of UAVs can be achieved. However, the dynamic properties of these systems and subsequently their manoeuvrability will change dramatically if a heavy load is suspended. A motivation for studying such a system configuration may come for example from the task of transporting of loads by UAVs during supply and rescue missions, often with very strict requirements on the delivery accuracy and safety.

The objective of the presented research is to enhance the control system of a UAV, a quadcopter in this particular case, with functionalities allowing to pre-compensate or efficiently damp the oscillatory modes brought by the suspended or flexibly attached loads. The given application serves as a case study for applying recent results by the research group achieved in flexible mode compensation by input shaping [1-3] and nonlinear oscillation damping schemes [4].

At the first stage a 2-D dynamic model of multibody mechanical system consisting of a quadcopter and a suspended load is studied. It consists of four second-order coupled nonlinear differential equations: two describing the translational x-y motion of the quadcopter, and the other two describing the absolute rotational motion of both the the quadcopter and the suspended load. After the model linearization and determining its dynamical modes, control loops for effective speed control in both horizontal and vertical directions are proposed. In order to pre-compensate the oscillatory mode in the horizontal motion, an inverse distributed delay shaper [1] is implemented within the loop. Compared to the feedforward application of input shaper, in the given architecture with inverse shaper, the oscillatory mode is pre-compensated not only in the set-point channel, but also in the channel from the system (quadcopter) disturbances. A crucial task to perform for the inverse shaper parametrization, is determining the oscillatory mode to be compensated. Interestingly, as derived in [2], the inverse shapers target mode does not belong to the set of modes of the multibody system. Instead, it is a mode of a modified model, with the controlled degree of freedom virtually fixed. The subsequent task is the parametrization of the position controller, in which an infinite order of the closed loop brought by the time delays in the shaper needs to be taken into account [3]. The final task is application of nonlinear time-delay based compensator scheme recently proposed in [4] to damp the pendulum oscillations by purely vertical motion of the quadcopter. This approach can be applied to damp the payload oscillations if the horizontal manoeuvrability of the quadcopter is restricted or not possible, e.g. due to physical obstacles in the planned trajectory, particularly in the final stage of the transport when the payload needs to be laid down on an exact position. Next to the outline of the theoretical approaches applied to design the control schemes with time delays, the results will be visualised on a simulator of quad-copter 2-D motion. The presented simulation based study is a preliminary step to the planned experimental verification, which will also be outlined.

[1] Vyhlídal T., Hromčík M., Kučera V., Anderle M., On Feedback Architectures With Zero-Vibration Signal Shapers, *IEEE Transactions on Automatic Control* **61**(8):2049–2064, 2016.

[2] Hromčík M., Vyhlídal T., Inverse Feedback Shapers for Coupled Multibody Systems, *IEEE Transactions on Automatic Control* **62**(9):4804–4810, 2017.

[3] Pilbauer D., Michiels W., Busek J., Osta D., Vyhlidal T., Control design and experimental validation for flexible multi-body systems pre-compensated by inverse shapers, *Systems & Control Letters*, accepted 2017.

[4] Vyhlídal T., Anderle M., Bušek J., Niculescu S. I., Time-Delay Algorithms for Damping Oscillations of Suspended Payload by Adjusting the Cable Length, *IEEE/ASME Transactions on Mechatronics* **22**(5):2319–2329, 2017.