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Point to Point Control of a Liquid Carrying Quadrotor

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ABSTRACT: Liquid transport by unmanned aerial vehicles is a necessary task in autonomous firefighting and field spraying missions. On the other hand, transient and residual sloshing of the liquid during and after the movement can cause instability, increase position error and control effort, and create danger or damage if the liquid is flammable. Therefore, in this study, control of a liquid carrier quadrotor has been studied and a controller has been presented that, unlike previous studies, can provide stability in point-to-point transmission without the need to measure or estimate liquid states. For this purpose, a controller is first designed by linearizing the equations of motion of the system and assuming the liquid is rigid via pole placement. On the other hand, in order for the behavior of the system to be similar to the behavior of the design model and to maintain the stability of the system, the liquid sloshing must be reduced as much as possible. Therefore, a command smoother based on the natural frequencies of the liquid sloshing modes is used. The ability of the proposed control system has been investigated, validated, and compared with a similar study by simulation. Also, the simulation results show that the implementation of the designed command smoother can significantly reduce the amplitude of liquid sloshing, the deviation of the system states from the equilibrium state, and the control effort.

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1- Introduction

Quadrotors have been among the main interests of scientists due to traits such as high maneuverability, the ability to hover, and vertical and take-off and landing [1]. This has caused the quadrotor's field of application to expand greatly. Today, some applications such as agricultural drones, refueling drones, and firefighting drones may demand quadrotors to carry a certain amount of liquid on board. However, as useful as it can be, liquid carrying quadrotors face many difficulties, one of which is the sloshing effect of the onboard liquid. The vibrations caused by the sloshing of the onboard liquid can affect the flight dynamics of the quadrotor and potentially can cause the drone to become unstable [2].

Many studies have been made on the case of suppressing liquid slosh. One approach is to implement passive methods which involve using baffles in liquid containers [3]. However, a study showed that using baffles is not capable of fully suppressing liquid sloshing [4]. Thus, using an active approach is much more suitable. One active method of suppressing liquid sloshing is to use open-loop schemes which involve generating a suitable trajectory that does not agitate the onboard liquid. Command smoothing is one such scheme which involves filtering the desired trajectory from frequencies that can excite the sloshing modes. Zang et al. [5] showed that using a command smoother to suppress liquid sloshing in containers is very effective.

The main purpose of this paper is to reduce the liquid sloshing while controlling the position of a liquid carrying quadrotor. The combined mathematical model of the liquid and drone was derived using Lagrange equations. This was done while the liquid was modeled as an infinite number of mass-spring-damper. A linear feedback position controller was designed based on the linearized equations of motion. A command smoother was designed based on the first natural frequency of the liquid sloshing to filter the desired command of the controller. In order to confirm the ability of the designed controller and command smoother in reducing the sloshing effects while maintaining the desired values for the quadrotor position, a simulation of the derived equations of motion was done using a combination of step inputs for the desired trajectory. Then, the results of the current simulation were compared to the results of another control scheme which was implemented on a liquid carrying quadrotor. The results of the simulation showed that the presented method can successfully reduce the sloshing effects of the onboard liquid while showing an acceptable performance on trajectory tracking. The results also showed that by reducing the sloshing effects of the liquid, the amount of control input to the system is reduced as well.

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2- Methodology

The equations of motion for the liquid carrying quadrotor were derived using Lagrange equations. Assuming small amplitudes of slosh, the liquid can be modeled as an infinite number of mass-spring-dampers [6]. The controller used to track the desired trajectory was designed based on a linear feedback scheme. In order to derive the control rule, the equations of motion had to be linearized around the hover point of the drone. In designing the controller, it was also assumed that the liquid is a solid mass. Controller gains were chosen such that the controller shows desirable trajectory tracking performance and the dominant poles of the closed-loop system become less than the first natural frequency of the liquid slosh. This way the controller is less likely to excite vibration modes of liquid. In order to suppress the sloshing effects of the liquid, a command smoother was designed based on the one presented in Ref. [7]. It uses the first natural frequency of the liquid sloshing and filters all frequencies higher than the first natural frequency. This way, the smoothed command does not excite higher frequencies of liquid sloshing. The command smoother is implemented by putting it before the controller, such that the desired control command is first filtered by the command smoother, then goes through the controller.

3- Results and Discussion

The simulations were done using a set of step inputs for the desired trajectory. The results were also compared with another controller which was used to control a liquid carrying quadrotor in Ref. [8]. The referenced controller was tuned in a way that the step response of the presented controller and the referenced controller are similar. Using the command smoother caused a small delay in the trajectory tracking performance of the controller. The command smoother was successful at reducing the liquid sloshing while the controller presented in Ref. [8], while successful at tracking the desired trajectory, caused a great amount of liquid sloshing. The controller presented in Ref. [8] also caused a great spike in control inputs which is undesirable. While the command smoother reduced the amount of control input by suppressing liquid slosh.

4- Conclusion

The main goal of this study was to reduce the sloshing in the liquid carrying quadrotor using the command smoother as an open-loop active scheme. The equations of motion were derived using Lagrange equations and a linear feedback controller was designed based on linearized equations of motion. The results of the simulation showed that the command smoother was successful at reducing the amount of liquid slosh. This reduction in slosh, however, comes with a small delay in tracking performance. This small cost is acceptable because reducing the amount of liquid slosh can be much more valuable in some cases. Also, the command smoother was able to reduce the amount of control input by reducing the liquid slosh. This can be very valuable as well since such drones rely heavily on limited energy storage.

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