Extended Results and Discussions [1]

Title: Multi-UAV Collaborative Transportation of Payloads with Obstacle Avoidance

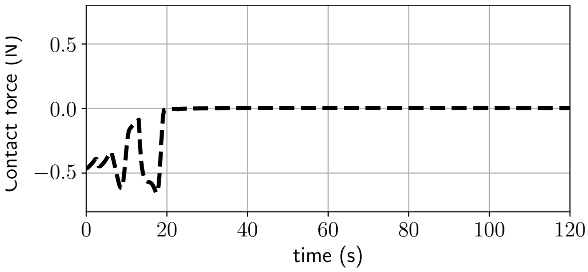
Robustness Study of the Payload Obstacle Avoidance Constraint

Although our simulated model does not explicitly show the contact force constraint satisfaction, please note that the assumption of a rigid payload ensures that the payload length is maintained, and that the achieved UAV velocities $\boldsymbol{v}_k$ satisfy the contact force constraint. However, the forces applied at the ends of the payload by the UAVs $\boldsymbol{f}_k = m_k \boldsymbol{a}_k$ may cause a contact force due to the velocity tracking errors. To verify the effects of the tracking errors we have simulated a few cases by making the gains K of the velocity controller $\boldsymbol{a}_k = K(\boldsymbol{u}_k - \boldsymbol{v}_k)$ on the two UAVs different. This leads to a non-zero difference in the components of the forces along the payload direction $(\boldsymbol{f}_1 - \boldsymbol{f}_2)^T \hat{\boldsymbol{p}}_{1,2}$, leading to contact forces (no/negligible deformation of the rigid payload).

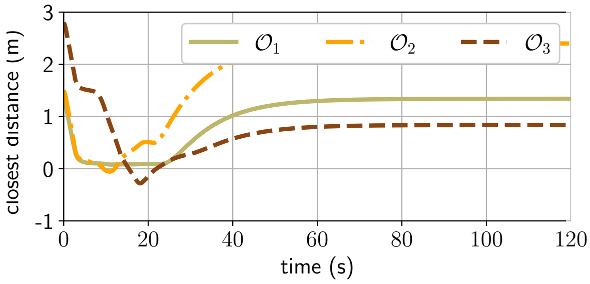
We make the following observations using the extended simulation results:

1. The consideration of the contact force constraint stabilizes the system and helps in obstacle avoidance. The case with no contact force constraint in the QP problem leads to collisions with Obstacles 2 and 3 as seen in Fig. 1(b) on the next page.
2. For the cases in which we consider the contact force constraint but have different values of K for the two UAVs, we observe obstacle avoidance despite seeing non-zero contact forces (see Figs. 1(d) and 1(f) on the next page).
3. For equal gains K of the velocity controllers on the UAVs (results presented in the paper), we see negligible/no contact forces, as the UAVs' responses are similar.

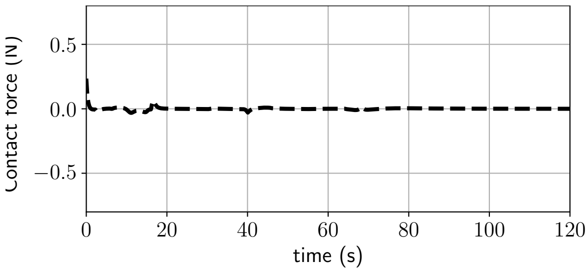
The above results show that the payload model that we have considered in our simulations, accounts for the contact forces implicitly, such that any push-pull forces along the payload direction in the absence of the contact force constraint, causes obstacle collisions. We also see that with different dynamics for the UAV accelerations (and payload ends), the collision avoidance constraint retains its robustness with the inclusion of the contact force constraint. Though the above results are a proxy for the dynamics introduced by the tracking errors of the UAV autopilot, they demonstrate that any such errors are handled sufficiently well by using the collision avoidance and contact force constraints together.



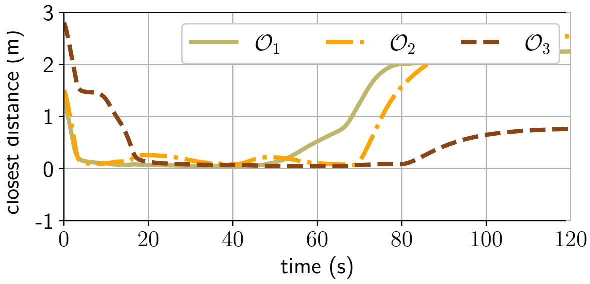
(a) Case 1: $(\boldsymbol{f}_1 - \boldsymbol{f}_2)^T \hat{\boldsymbol{p}}_{1,2}$, when no contact force constraint is considered in the QP problem.



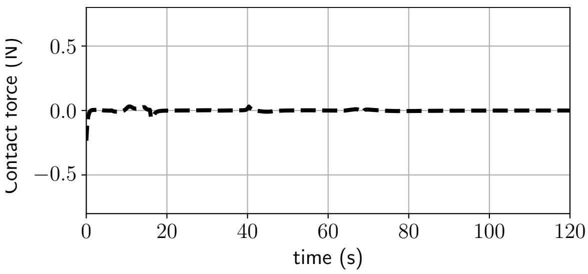
(b) Case 1: Obstacle distances when no contact force constraint is considered in the QP problem.



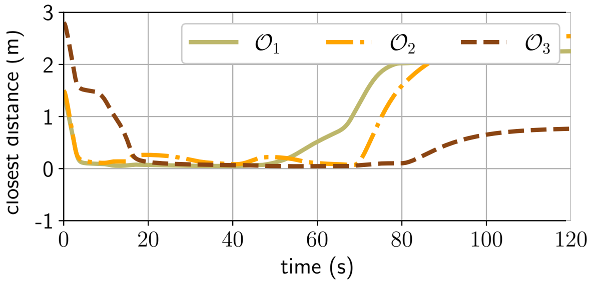
(c) Case 2a: $(\boldsymbol{f}_1 - \boldsymbol{f}_2)^T \hat{\boldsymbol{p}}_{1,2}$, when the contact force constraint is considered in the QP problem, $K = 1$ for UAV 1 and $K = 2$ for UAV 2.



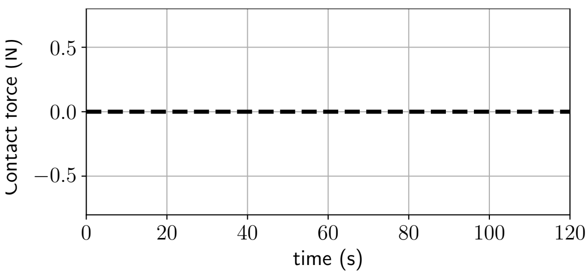
(d) Case 2a: Obstacle distances when the contact force constraint is considered in the QP problem, $K = 2$ for UAV 1 and $K = 1$ for UAV 2.



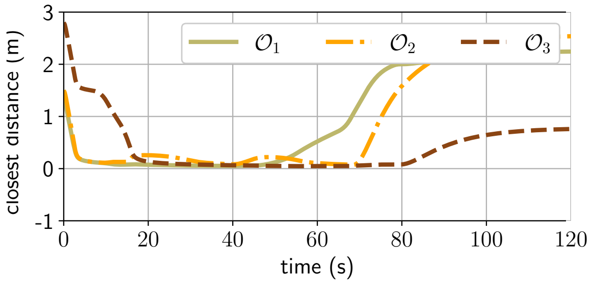
(e) Case 2b: $(\boldsymbol{f}_1 - \boldsymbol{f}_2)^T \hat{\boldsymbol{p}}_{1,2}$, when the contact force constraint is considered in the QP problem, $K = 1$ for UAV 1 and $K = 2$ for UAV 2.



(f) Case 2b: Obstacle distances when the contact force constraint is considered in the QP problem, $K = 2$ for UAV 1 and $K = 1$ for UAV 2.



(g) Case 3: $(\boldsymbol{f}_1 - \boldsymbol{f}_2)^T \hat{\boldsymbol{p}}_{1,2}$, when the contact force constraint is considered in the QP problem and $K = 2$ for both UAVs.



(h) Case 3: Obstacle distances when the contact force constraint is considered in the QP problem and $K = 2$ for both UAVs.

Figure 1: Contact forces and obstacle distances for different cases.

Dimensions of the Payload and UAVs

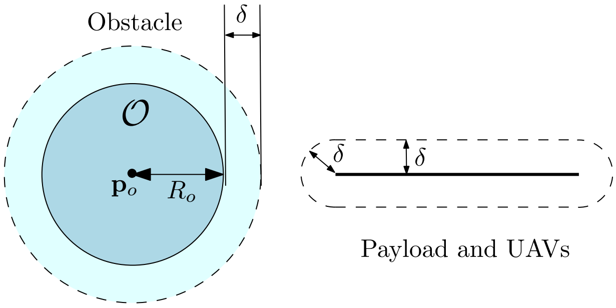


Figure 2: The payload and UAV dimensions can be accounted for by enclosing them in a closed convex curve with width of δ around the center-line. Equivalently the radius of the ball enclosing the obstacle can be increased to $R_o + \delta$, and the payload can be considered to be a line, as in our analysis.

The dimensions/size of the payload can be accounted for by enclosing the UAVs and payload in a circle/ellipse/rectangle. The payload dimensions can also be accounted for by increasing the dimensions of the balls enclosing the obstacles, and considering the payload (and attached UAVs) as a line (please see Fig. 2 in this document).

References

[1] A. Hegde and D. Ghose, "Multi-UAV collaborative transportation of payloads with obstacle avoidance," *Submitted for publication*, 2021.