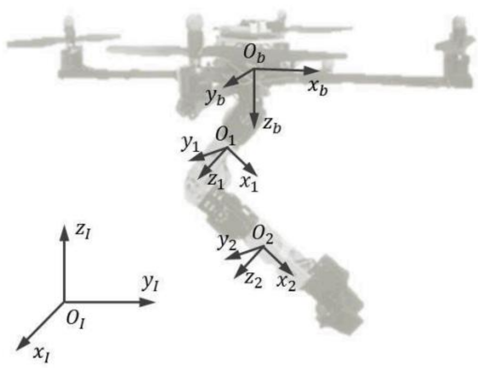
Aerial Manipulation Using a Quadrotor with a Two DOF Robotic Arm

Overview – The paper presents an aerial manipulation system using a quadrotor with a two-degree-of-freedom (DOF) robotic arm. By considering the quadrotor and robotic arm as an integrated system, the authors developed a kinematic and dynamic model and designed an adaptive sliding mode controller to enable autonomous flight that includes object pick-up and delivery. The system demonstrates potential applications in tasks such as inspection, manipulation, and transportation in remote areas.

Objective of the paper -

The primary objective of the paper is to develop a control system that can manage a quadrotor and a two-DOF robotic manipulator as a unified system (coupled system) to perform aerial manipulation tasks. Existing approaches have limitations, such as restricted payload attitude, limited range of manipulation, or lack of direct control over the payload. To overcome these challenges, the authors propose equipping an aerial vehicle with a robotic manipulator that can actively interact with the environment and using *Adaptive Sliding Mode Controller*.

Dynamics –



$$\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{q}} - \frac{\partial \mathcal{L}}{\partial q} = \tau + \tau_{ext}$$

$$\mathcal{L} = \mathcal{K} - \mathcal{U}$$

$$q = [p^T \;\; \Phi^T \;\; \eta^T]^T$$

Here q is vector of coordinate variables such that $p = [x \; y \; z]^T$ (position of quadrotor in inertial frame), $\Phi = [\phi \; \theta \; \psi]^T$ (euler angles) and $\eta = [\eta_1 \; \eta_2]^T$ (manipulator joint angles).

$$
\begin{aligned}
\dot{p} &= [I_{3\times3} \quad 0_{3\times3} \quad 0_{3\times2}]\dot{q} = M_{t,b}\dot{q} \\
\omega &= [0_{3\times3} \quad T \quad 0_{3\times2}]\dot{q} = M_{r,b}\dot{q} \\
\dot{p}_i &= [I_{3\times3} \; -(R_t p_i^b)^\wedge T \quad R_t J_{t,i}]\dot{q} = M_{t,i}\dot{q} \\
\omega_i &= [0_{3\times3} \quad T \quad R_t J_{r,i}]\dot{q} = M_{r,i}\dot{q}
\end{aligned}
$$

$$
\begin{bmatrix} F \\ \tau_x \\ \tau_y \\ \tau_z \\ \tau_\eta \end{bmatrix} = \begin{bmatrix} R_t(3,3) & 0 & 0 \\ 0 & Q^{-1} & 0 \\ 0 & 0 & I_{2\times2} \end{bmatrix}^{-1} \begin{bmatrix} \tau(3) \\ \vdots \\ \tau(8) \end{bmatrix}
$$

Here F is net thrust on quadrotar anf Tx, Ty, Tz are torques applied on quadrotor and Tn are the torques applied on manipulator joints.

Here the final combined dynamics of quadrotar and manipulator can be written as -

$$
M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau + \tau_{ext}
$$

Adaptive Sliding Mode Controller –

Adaptive Sliding Mode Control (ASMC) combines the benefits of sliding mode control (SMC) with adaptive control techniques. It is particularly well-suited for systems that experience uncertainties or external disturbances, such as robotic manipulators, aerial vehicles, or other nonlinear dynamic systems.

Sliding Mode Control –

Sliding mode control is a robust control technique used for nonlinear systems. The main idea of SMC is to drive the system state to a predefined "sliding surface" and keep it there. This approach ensures that the system follows the desired behaviour despite uncertainties or external disturbances. The main features of SMC are –

1. Sliding Surface
2. Control Law
3. Robustness

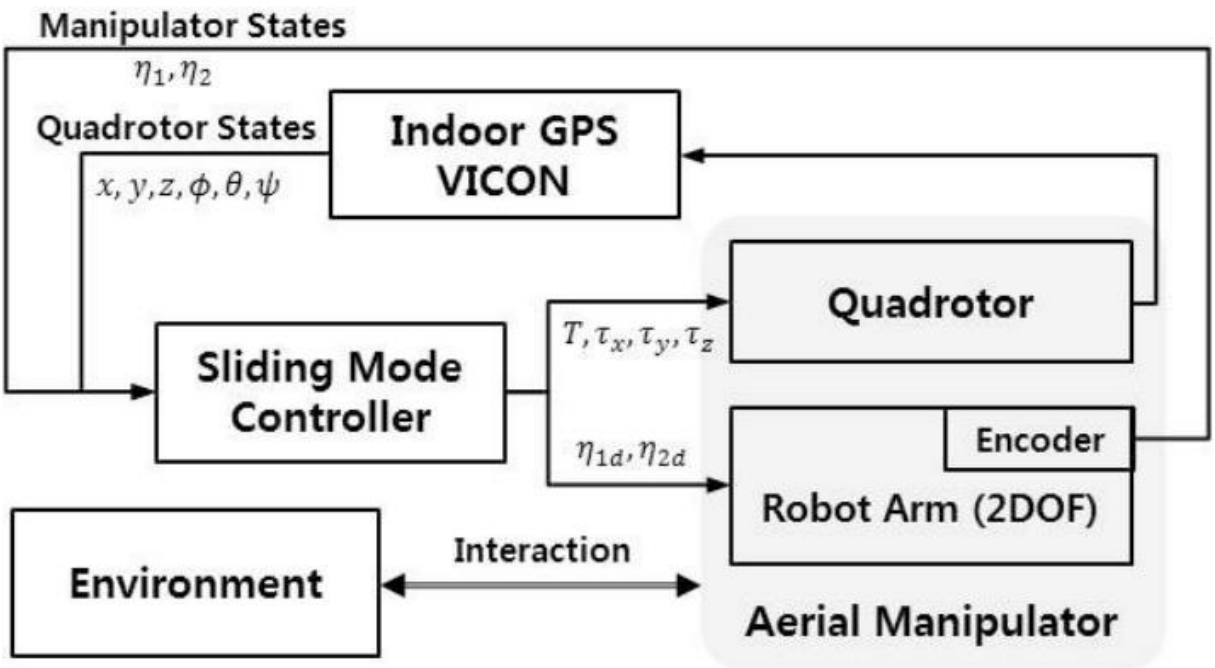
Existing approaches have limitations, such as restricted payload attitude, limited range of manipulation, or lack of direct control over the payload. To overcome these challenges, the authors propose equipping an aerial vehicle with a robotic manipulator that can actively interact with the environment and using *Adaptive Sliding Mode Controller*.

Here ASMC is used mainly to handle the highly coupled dynamics (non-linear dynamics) and the uncertainties in the system (mainly caused during picking, dropping and moving an object using manipulator).

$$\begin{aligned} e &= q - q_d \\ s &= \dot{e} - \Lambda e \\ \dot{q}_r &= \dot{q} - s = \dot{q}_d - \Lambda e \end{aligned}$$

The proposed control law for t is - $\tau = \hat{M}\ddot{q}_r + \hat{C}\dot{q}_r + \hat{G} + \hat{\Delta} - As - K\mathbf{sgn}(s)$

Here A, G are positive gain matrices and *M^, C^ and G^* are estimation of each matrix and Δ^ is estimation of uncertainty.



Future work – We will be exploring different control laws which can be applied to this system mainly in two cases – treating the dynamics of quadrotor and manipulator coupled, treating the dynamics uncoupled.