Aerial Transportation and Manipulation of a Cable-Slung Payload with Decentralized Swarm Agents

Aniket Sharma*, **Nandan K. Sinha**†

*Aerospace Engineering Department
Indian Institute of Technology Madras
Chennai 600036, India
aniketsharma0112@gmail.com

†Aerospace Engineering Department
Indian Institute of Technology Madras
Chennai 600036, India
nandan@ae.iitm.ac.in

Abstract
The application of Unmanned Aerial Vehicles (UAV) and Micro Aerial Vehicles (MAV) for transportation and delivery systems has attracted many research works. A swarm of agents, cooperatively working to transport a payload can overcome the physical limitations of a single agent, adding redundancy and tolerance against failures. A coordinated swarm can also manipulate the payload's orientation by using the principles of parallel manipulators [1]. The complexity and computational cost of the multi-agent system is higher than a monolithic system when studied in a centralized architecture. This work proposes a decentralized control scheme for the swarm of agents to carry out the transportation and manipulation of a payload. The *emergent* behaviour of a decentralized swarm formation carries out the macro scale task while depending only on local interaction between agents. This makes the complexity of the control law for an agent independent of the size of swarm; resulting in a more scalable and flexible system. The feasibility of a swarm system engenders from the group behaviour of simple and cost-effective individual agents. Keeping this in focus, the formation laws proposed in this work are independent of the state information of the payload, discarding the need of vision or other sensor information to detect payload position and orientation on each agent. A survey on aerial transportation using cooperative multiple aerial manipulators is presented in [2]. Cable based manipulators are the focus in this study. The interaction between the payload and agents has been modelled as kinematic constraints in [1] and as flexible massless spring models in [3]. However, the deformation of the cables cannot be observed with geometric or massless spring model. The cable model in this work consists of a series of lumped masses of cable elements connected *via* spring-damper systems. A schematic of this multi-body system is shown in Figure 1. The superscript of vectors describes the frame of reference, I for the inertial reference frame

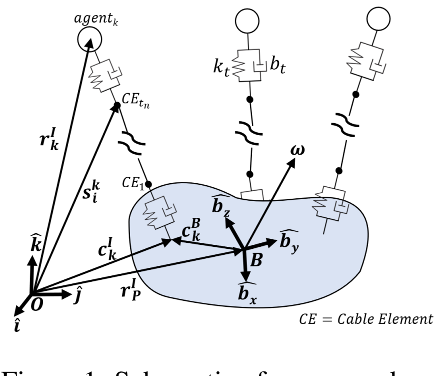


Figure 1: Schematic of swarm and payload system

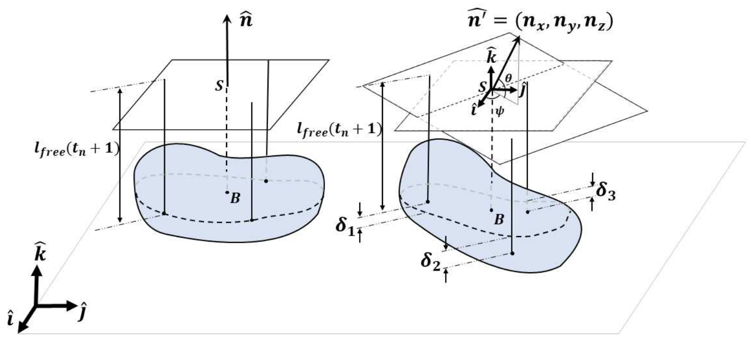


Figure 2: Manipulation of the payload

($\mathscr{F}^{\mathscr{I}}$) and B for the payload body-fixed reference frame ($\mathscr{F}^{\mathscr{B}}$). A transformation matrix, ${}^{\boldsymbol{I}}\boldsymbol{T}^{\boldsymbol{B}}$, maps vectors from $\mathscr{F}^{\mathscr{B}}$ to $\mathscr{F}^{\mathscr{I}}$ frame. A rigid body payload of mass m_P and mass moment of inertia I_P is attached to each agent of a swarm (of size n) *via* cables. The anchor point of k^{th} cable on the payload is a constant vector $\boldsymbol{c_k^B}$ in $\mathscr{F}^{\mathscr{B}}$. This cable is modelled as a series of t_n *Cable Elements* (CE) where the spring-mass-damper interaction between i^{th} and j^{th} CE is governed by Equation (1).

$$\boldsymbol{f}(\boldsymbol{s_i^k},\boldsymbol{s_j^k},\dot{\boldsymbol{s}}_{\boldsymbol{i}}^{\boldsymbol{k}},\dot{\boldsymbol{s}}_{\boldsymbol{j}}^{\boldsymbol{k}}) = -\alpha(\Delta s_{ij}^k)\times\left(k_t\Delta s_{ij}^k + b_t\frac{\boldsymbol{s_{ij}^k}\cdot\dot{\boldsymbol{s}}_{\boldsymbol{ij}}^{\boldsymbol{k}}}{\|\boldsymbol{s_{ij}^k}\|}\right)\frac{\boldsymbol{s_{ij}^k}}{\|\boldsymbol{s_{ij}^k}\|} \tag{1}$$

where $\alpha(x) = \left\{\begin{array}{ll} 1, & \text{for } x>0 \\ 0, & \text{otherwise}\end{array}\right\}$ is a scalar function which models slacking of the cable, $\boldsymbol{s_{ij}^k} = \boldsymbol{s_i^k} - \boldsymbol{s_j^k}$, $\dot{\boldsymbol{s}}_{\boldsymbol{ij}}^{\boldsymbol{k}} = \dot{\boldsymbol{s}}_{\boldsymbol{i}}^{\boldsymbol{k}} - \dot{\boldsymbol{s}}_{\boldsymbol{j}}^{\boldsymbol{k}}$, $\Delta s_{ij}^k = \|\boldsymbol{s_{ij}^k}\| - l_{free}$ and l_{free} is the nominal length of a single cable element.

Cable dynamics: Using Equation (1), for CE $i = 2,3,...,t_n-1$,

$$m_i^k\ddot{\boldsymbol{s}}_{\boldsymbol{i}}^{\boldsymbol{k}} = \boldsymbol{f}(\boldsymbol{s_i^k},\boldsymbol{s_{i+1}^k},\dot{\boldsymbol{s}}_{\boldsymbol{i}}^{\boldsymbol{k}},\dot{\boldsymbol{s}}_{\boldsymbol{i+1}}^{\boldsymbol{k}}) + \boldsymbol{f}(\boldsymbol{s_i^k},\boldsymbol{s_{i-1}^k},\dot{\boldsymbol{s}}_{\boldsymbol{i}}^{\boldsymbol{k}},\dot{\boldsymbol{s}}_{\boldsymbol{i-1}}^{\boldsymbol{k}}) - m_i^k\boldsymbol{g} \tag{2}$$

For CE $i = t_n$ and $i = 1$, $\boldsymbol{s^k_{i+1}} = \boldsymbol{r^I_k}$ and $\boldsymbol{s^k_{i-1}} = \boldsymbol{c^I_k}$ respectively in Equation (2).

Payload dynamics:

$$m_P \ddot{\boldsymbol{r}}^{\boldsymbol{I}}_{\boldsymbol{P}} = -c\dot{\boldsymbol{r}}^{\boldsymbol{I}}_{\boldsymbol{P}} + \sum_{k=1}^{n} \left(\boldsymbol{f}(\boldsymbol{c^I_k}, \boldsymbol{s^k_1}, \dot{\boldsymbol{c}}^{\boldsymbol{I}}_{\boldsymbol{k}}, \dot{\boldsymbol{s}}^{\boldsymbol{k}}_{\boldsymbol{1}}) \right) - m_P \boldsymbol{g}$$
$$\boldsymbol{I_P}\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega} \times (\boldsymbol{I_P}\boldsymbol{\omega}) + \boldsymbol{M} \tag{3}$$

where c is a dissipation coefficient due to drag and $\boldsymbol{M} = \sum_{k=1}^{n} \left({}^{\boldsymbol{I}}\boldsymbol{T}^{\boldsymbol{B}} \boldsymbol{c^B_k} \times \boldsymbol{f}(\boldsymbol{c^I_k}, \boldsymbol{s^k_1}, \dot{\boldsymbol{c}}^{\boldsymbol{I}}_{\boldsymbol{k}}, \dot{\boldsymbol{s}}^{\boldsymbol{k}}_{\boldsymbol{1}}) \right)$ is the external moment on the payload about B in $\mathscr{F}^{\mathscr{I}}$.

Swarm dynamics: For a swarm agent k,

$$m\ddot{\boldsymbol{r}}^{\boldsymbol{I}}_{\boldsymbol{k}} = -c\dot{\boldsymbol{r}}^{\boldsymbol{I}}_{\boldsymbol{k}} + \boldsymbol{f}(\boldsymbol{r^I_k}, \boldsymbol{s^k_{t_n}}, \dot{\boldsymbol{r}}^{\boldsymbol{I}}_{\boldsymbol{k}}, \dot{\boldsymbol{s}}^{\boldsymbol{k}}_{\boldsymbol{t_n}}) + \boldsymbol{u_k}(\boldsymbol{r^I_k}) - m\boldsymbol{g} \tag{4}$$

where $\boldsymbol{u_k}(\boldsymbol{r^I_k})$ is the control input for swarm agent k. For some time t, position of agent k is $\boldsymbol{r^I_k} = [x_k, y_k, z_k]^T$ and $\boldsymbol{r^I_g} = [x_g, y_g, z_g]^T$ be some goal set point of the payload. The swarm tracks a center, S, with position vector $\boldsymbol{p^I}$. Let desired azimuth and elevation angle of the swarm formation plane (also for the payload) be ψ and θ respectively. An $x-y$ plane at a height of $z_g + L$ is proposed as an attractor for the swarm with increments/decrements of δ_k to control the azimuth and elevation angles of the payload (shown in Figure 2 (right)). Let $\boldsymbol{\Delta^k} = \boldsymbol{r^I_k} - \boldsymbol{p^I} = [\Delta^k_x, \Delta^k_y, \Delta^k_z]^T$ and $\|\Delta^k_{xy}\| = \sqrt{\Delta^{k2}_x + \Delta^{k2}_y}$ for k^{th} agent. The attractor for the swarm is,

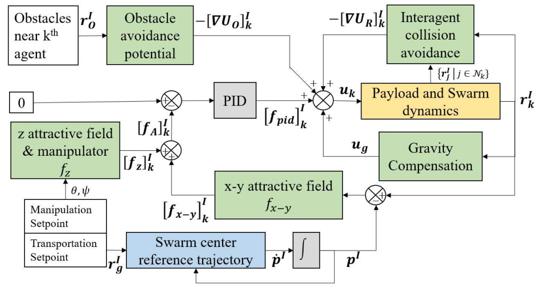


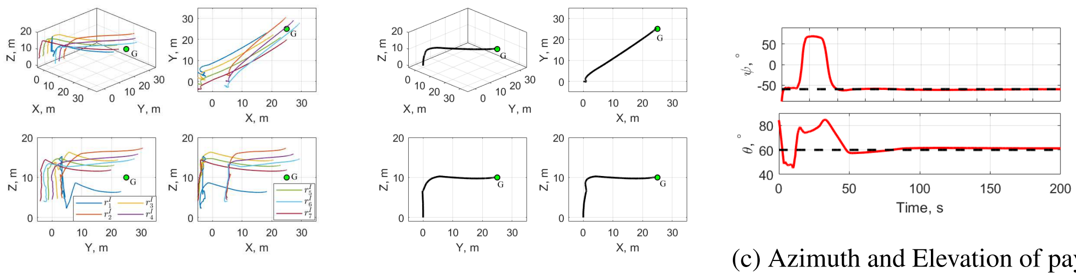
Figure 3: Block diagram of swarm formation control

$$[\boldsymbol{f_A}]^{\boldsymbol{I}}_{\boldsymbol{k}} = \left(1 - \frac{(1+e^{\beta})^2}{(1+e^{-\|\Delta^k_{xy}\|+\beta})(1+e^{\|\Delta^k_{xy}\|+\beta})} \frac{1}{\|\Delta^k_{xy}\|}\right) \begin{bmatrix} \Delta^k_x \\ \Delta^k_y \\ 0 \end{bmatrix} + k_z\left(z_k - (z_g + L + \delta_k(\theta, \psi))\right) \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{5}$$

where k_z, β are gain constants and $L = l_{free}(t_n + 1)$. This formation control signal $[\boldsymbol{f_A}]^{\boldsymbol{I}}_{\boldsymbol{k}}$ is passed through a PID block ($[\boldsymbol{f}_{pid}]^{\boldsymbol{I}}_{\boldsymbol{k}}$), as shown in Figure 3, to ensure tracking of the formation shape in presence of external disturbances and irregular mass/swarm distribution. Equation (6) is the decentralized swarm formation control law with interagent collision avoidance and obstacle avoidance potential gradients.

$$\boldsymbol{u_k}(\boldsymbol{r^I_k}) = \left(\frac{m_P}{n} + m\right)\boldsymbol{g} + [\boldsymbol{f}_{pid}]^{\boldsymbol{I}}_{\boldsymbol{k}} - \nabla\left(\sum_{\boldsymbol{r^I_j} \in \mathscr{N}_k} C_R e^{\frac{-\|\boldsymbol{r^I_k} - \boldsymbol{r^I_j}\|}{L_R}}\right) - \nabla\left(\sum_{\boldsymbol{r^I_o} \in \mathscr{O}} C_o e^{\frac{-\|\boldsymbol{r^I_k} - \boldsymbol{r^I_o}\|}{L_o}}\right) \tag{6}$$

$\mathscr{N}$ and $\mathscr{O}$ are set of neighbouring agents and obstacles for agent k respectively. C_R, L_R, C_O, and L_O are constants and $\boldsymbol{g} = [0, 0, 9.8]^T$. The efficacy of the method proposed are evaluated through numerical simulations (MATLAB ode45) under influence of external disturbances and failure of agents (Figure 4).



(a) Swarm agents trajectory (b) Payload trajectory (c) Azimuth and Elevation of payload

Figure 4: Payload Transportation and Manipulation with failure of Agent 1 at t = 10s

References

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