Cooperative Object Transport in 3D with Multiple Quadrotors using No Peer Communication

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Abstract—We present a framework to enable a fleet of rigidly attached quadrotor aerial robots to transport heavy objects along a known reference trajectory without inter-robot communication or centralized coordination. Leveraging a distributed wrench controller, we provide exponential stability guarantees for the entire assembly, under a mild geometric condition. This is achieved by each quadrotor independently solving a local optimization problem to counteract the biased torque effects from each robot in the assembly. We rigorously analyze the controllability of the object, design a distributed compensation scheme to address these challenges, and show that the resulting strategy collectively guarantees full group control authority. To ensure feasibility for online implementation, we derive bounds on the net desired control wrench, characterize the output wrench space of each quadrotor, and perform subsequent trajectory optimization under these input constraints. We thoroughly validate our method in simulation with eight quadrotors transporting a heavy object in a cluttered environment subject to various sources of uncertainty, and demonstrate the algorithm’s resilience.

I. INTRODUCTION

In this paper, we present a distributed controller that allows a group of rigidly-attached quadrotor aerial robots to cooperatively transport heavy objects in 3D. Distinct from existing cooperative aerial manipulation literature, our approach addresses the challenging problem where no peer communication is allowed among the robots. The only available information to each individual robot are the inertial properties of the object, its attachment point on the object, and a reference trajectory that is broadcast to all robots. Notably, the robots do not know the locations, nor the actions taken by other robots. Instead, each quadrotor locally solves an independent optimization problem at each time-step, and a reference trajectory that is broadcast to all robots. Notably, the robots do not know the locations, nor the actions taken by other robots. Instead, each quadrotor locally solves an independent optimization problem at each time-step, the collective result of which guarantees the desired group behavior. By eliminating the communication bottleneck, which has been shown to be noisy, vulnerable, complicated and non-scalable in large swarm systems [1], our method is suitable for a broad range of applications that require fast response, quick setup, and frequent reconfiguration. For example, in a disaster relief scenario, our approach can be used as a modular system to deliver equipment of various sizes, by utilizing up to tens or hundreds of drones at a time. In the civil sector, packages can be delivered in the most efficient and economical way by matching the size of the package with the required number of robots.

Our controller is based upon the SE(3) geometric controller and differential flatness theory [2], [3], [4], which are powerful tools for controlling a single quadrotor. In our method, each quadrotor takes equal responsibility for the desired nominal wrench for the object with respect to its center of mass, computed independently by each quadrotor. This nominal wrench is usually not feasible for a single quadrotor due to its inherent biased torque controllability. Through a decomposition into unbiased axes and biased axis (see Figure 3 for an illustration), we show that three components of the 4D nominal wrench are feasible for a single quadrotor. A local optimization is then solved by each quadrotor to best realize the desired moment along the biased axis while still adhering to the three feasible components of the nominal wrench along the unbiased axes.

Under a mild centrosymmetric condition (Assumption 1), we show that the proposed control strategy is exponentially stable and is tolerant of non-centrosymmetric robot configurations as well. We perform thorough analysis of the feasibility of the controller, where we derive explicit bounds on the required thrust and moments and characterize each quadrotor’s wrench output space. Finally, we leverage bilevel constrained trajectory optimization to compute snap-and-time-optimal paths that satisfy the computed control bounds and solve the problem using an exterior point method and iterative coordinate descent.

Our work is related to a number of cooperative object transport methods for 2D planar motion that also do not require explicit inter-robot communication [5], [6], [7], [8], [9], and [10] where decentralized adaptive control is used for ground robots. Our solution to the 3D case greatly

Fig. 1. An example of object transport in 3D with six quadrotors, which are rigidly attached to the object. The quadrotors do not communicate with each other, thus allowing for fast reconfiguration for objects of different sizes. This is achieved by each quadrotor independently computing their control action onboard based on a reference trajectory that is broadcast to them.

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broadens the allowable workspace. In terms of cooperative aerial manipulation, a centralized control allocation approach is presented in [11] for a group of rigidly attached quadrotors. A tele-manipulation framework using multiple UAVs is proposed in [12] by translating hand motion into quadrotor formation and interaction force control. Other researchers have considered using cables to suspend the payload by multiple aerial robots [13], [14], [15]. However, in many applications it is impractical to connect a large number of cables to a payload. In package delivery or autonomous construction applications where significant aerial traffic is expected, entangled cables and collisions between swinging payloads becomes a concern. In [16] and [17], the quadrotors are augmented with 2-DOF robotic arm and the problems are addressed from the perspective of path planning and decentralized flatness-based control. A formation-based cooperative manipulation approach is presented in [18]. Finally, our work is also inspired by trajectory generation methods for quadrotors in [19], [20]. However, our approach goes beyond the existing state-of-the-art by guaranteeing exponentially stable closed-loop tracking using decentralized feedback control in a significantly more challenging constrained setting.

The main contribution of this paper is threefold. First of all, we propose a decentralized wrench controller for cooperative aerial manipulation without peer communication (Section III). Under a mild centro-symmetric condition (Assumption 1), we show that exponential stability can be achieved on the position and attitude of the object, based on a pairwise controllability analysis. Secondly, in Section IV, we conduct a feasibility analysis on the online execution of our control algorithm. Bounds on position and attitude error, as well as the required thrust and torques are explicitly given. Finally, given the bounds from feasibility analysis, we solve the trajectory optimization problem (Section V) under input thrust and torque constraints, by leveraging differential flatness that allows us to compute open-loop state trajectory and reference inputs. Simulation results are presented in Section VI and successfully validate our proposed approach.

II. PROBLEM FORMULATION

We intend to use a group of quadrotors to collectively manipulate a heavy object, which has mass \( m \) and inertia tensor \( J \). The motion of the object in 3D space is governed by the Newton-Euler equations. Denote the 12-dimensional state variable as \( \xi = (x, y, z, v_x, v_y, v_z, \phi, \theta, \psi, p, q, r) \), corresponding to the 3D inertial position \( \mathbf{h} := (x, y, z) \), linear velocities \( \mathbf{v} := (v_x, v_y, v_z) \), Euler angles \( (\phi, \theta, \psi) \) and (body-frame) angular velocities \( \omega := (p, q, r) \). We adopt the “z down” body frame convention as shown in Figure 2 and the ZYX Euler angle rotation sequence.

Consider a fleet of \( N \) quadrotors, each rigidly attached to the object with their body z-axis aligned with that of the object. We assume that each individual quadrotor does not have sufficient power to lift the object. Let \( \mathbf{f} = [f_1, f_2, f_3, f_4]^T \) denote the thrust forces corresponding to quadrotor \( i \)’s four propellers, subject to the limits

\[
0 \leq f_i^j \leq f_{\text{max}}, \quad i \in \{1, \ldots, N\}, \quad j \in \{1, 2, 3, 4\}.
\]

Each quadrotor can generate a net thrust and three independent moments and will contribute a fraction of the total required wrench. The net resultant wrench due to quadrotor \( i \) expressed in its own body aligned frame is given by

\[
\mathbf{w}_{\text{quad}}^i := \begin{pmatrix} 1 & 1 & 1 & \frac{f_i^1}{f_{\text{max}}} \\ -r & r & -r & 0 \\ c & c & -c & 0 \end{pmatrix},
\]

where \( r \) is the moment arm length of each motor with respect to the quadrotor center of mass (see Figure 2), and \( c \) is a constant coefficient for the induced torque of the motor. The quadrotors are assumed to be attached to the x-y plane of the object with distance \( d_i \) and angle \( \alpha_i \in [-\pi, \pi] \) measured with respect to the object x-axis, as shown in Figure 1. The wrench imparted by quadrotor \( i \) to the object is given by

\[
\mathbf{w}_{\text{obj}}^i := \left( f_i^2, \tau^z \right) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ -d_i \sin \alpha_i & 1 & 0 & 0 \\ d_i \cos \alpha_i & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \mathbf{w}_{\text{quad}}^i,
\]

where without loss of generality, we have assumed that all individual quadrotor frames are aligned with the object’s frame.

Under the combined wrench inputs from all quadrotors, \( \mathbf{w}_{\text{obj}} := \sum_{i=1}^N \mathbf{w}_{\text{obj}}^i =: (\mathbf{f}, \tau) \), the equations of motion of the object are given as

\[
\dot{\mathbf{v}} = \mathbf{g} \mathbf{e}_3 - \frac{1}{m} R \mathbf{f} \mathbf{e}_3, \quad (3)
\]

\[
\dot{\mathbf{h}} = \mathbf{v}, \quad (4)
\]

\[
\dot{\omega} = J^{-1} \tau - J^{-1} \dot{\omega} J \omega, \quad (5)
\]

\[
\dot{R} = R \hat{\omega}, \quad (6)
\]

where \( \dot{\mathbf{e}}_3 \) is the body-to-inertial rotation matrix for the Euler angles \( (\phi, \theta, \psi) \), \( \mathbf{g} \) is the gravitational acceleration, \( \mathbf{e}_3 := [0, 0, 1]^T \), and \( \hat{\cdot} : \mathbb{R}^3 \rightarrow \mathfrak{so}_3 \) is the hat map transporting vectors in \( \mathbb{R}^3 \) to the SO(3) Lie algebra, \( \mathfrak{so}_3 \), the set of skew-symmetric matrices. In order to transport the object to the desired goal location, we assume that a smooth reference trajectory (continuously differentiable in time up to fourth order) is broadcast to all quadrotors. However, no peer communication is available between any two quadrotors. We also assume that each quadrotor knows the net mass \( m \), inertia \( J \), and number of quadrotors \( N \), as well as its attachment point on the object, i.e., the value of \( d_i \) and \( \alpha_i \). It does not, however, know
the locations of other quadrotors. Finally, we assume each quadrotor can measure the position, orientation, linear, and angular velocity of the object using onboard sensors.

III. DISTRIBUTED WRENCH CONTROL

Since all quadrotors have access to the reference trajectory and real-time state of the object, they can independently compute the total wrench required to track the trajectory. Since the combined payload and quadrotors is a rigid body with applied forces and torques, its dynamics resemble those of a single quadrotor, hence we will leverage the SE(3) controller first proposed in [2], [3] to compute the net object wrench. However, input constraints prohibit one individual quadrotor from exerting the required total wrench. In this section, we propose a distributed controller that allows each quadrotor to compute locally optimal control inputs, given no communication with any other quadrotor. Collectively, this locally optimal strategy results in a provably stable group behavior that guarantees successful tracking.

We first briefly review the SE(3) controller. Let \( \sigma : \mathbb{R}^3 \rightarrow \mathbb{R}^3 \) denote the reference position trajectory, continuously differentiable up to fourth order and \( \sigma_p : \mathbb{R}^3 \rightarrow S^1 \) the reference yaw trajectory, continuously differentiable up to second order. Given the current state of the object, the net desired thrust \( f_z \) and torque \( \tau \) are given by:

\[
\begin{align*}
    f_z &= -\left( -K_p e_p - K_v e_v - mg e_3 + m \ddot{\sigma} \right) R e_3, \quad (7) \\
    \tau &= -K_R e_R - K_\omega e_\omega + \dot{\sigma} \omega + J \left( -\dot{\omega} R^T \dot{R} e_3 e_\omega + \dot{R} R e_3 \dot{e}_\omega \right),
\end{align*}
\]

where

\[
\begin{align*}
    e_p &= h - \sigma, \\
    e_v &= v - \dot{\sigma}, \\
    e_R &= \frac{1}{2} \left( R e_3 e_R - R^T R e_3 \right) v, \\
    e_\omega &= \omega - R^T R e_3 \dot{\sigma}.
\end{align*}
\]

\((\cdot)^v : \mathbb{R}^3 \rightarrow \mathbb{R}^3\) is the inverse hat map, and \(K_p, K_v, K_R, K_\omega\) are diagonal feedback gain matrices. The desired rotation matrix \( R_{des} \) is defined by the desired z-axis \( z_0 := -F_{des}/\|F_{des}\| \), and desired yaw angle \( \sigma_\psi \). The desired angular velocity \( \dot{\omega}_{des} \) and acceleration \( \ddot{\omega}_{des} \) are defined by the time-derivatives of \( z_0 \) (thereby incorporating acceleration and jerk feedback) and \( \sigma_\psi \). Refer to [3] for a derivation of these quantities.

A. Wrench Allocation

In order to achieve the desired net wrench on the object as determined by the SE(3) controller, one needs to effectively assign desired motor thrusts to each quadrotor. This is a challenging problem for two reasons: (1) a quadrotor does not know the positions of other quadrotors, and cannot communicate with them, and (2) each quadrotor’s applied wrench is significantly biased about one axis due to its off-center attachment point. Consequently, their thrusts may induce large torques due to their respective moment arms. To address the first challenge, we assume that each quadrotor takes on equal responsibility for the net thrust \( f_z \) and torque \( \tau \); that is, the wrench command to the \( i \)th quadrotor expressed in the object’s frame is given by

\[
w_{i, obj} = \left( f_z/N, \tau/N \right),
\]

where each robot computes the SE(3) controller given in eqs. (7) and (8) in the object’s frame independently. Second, we introduce the following mild assumption regarding the arrangement of the quadrotors on the object:

Assumption 1 (Centro-symmetry). The robots attachment points are centroymmetric around the center of mass of the object, meaning that for any robot \( i \), there exists another robot \( j \neq i \), such that \( \alpha_j = \alpha_i - \pi \) and \( d_i = d_j \).

In practice, although it might be hard to strictly satisfy this assumption, the robots are likely to evenly spread out as the number of the robots increases [1] such that the assumption is approximately true. In addition, the symmetric configuration is an intuitive way for a user to attach the robots to a payload. Centro-symmetry is required for our analysis, but in practice our controller still works well if the assumption is violated, as explored in simulation in Section VI.

Given the pairwise centro-symmetry assumption, it will be useful to introduce a local reference frame for each quadrotor, hereby referred to as the local control frame, defined by simply rotating the object reference frame around the z-axis by angle \( \alpha_i \); see Figure 3 for an illustration. Then, the desired wrench for quadrotor \( i \) in its local control frame may be expressed using the following rotation:

\[
\begin{align*}
    c_R &= \begin{bmatrix} 1 & 0 & 0 & 0 \\
    0 & \cos \alpha_i & \sin \alpha_i & 0 \\
    0 & -\sin \alpha_i & \cos \alpha_i & 0 \\
    0 & 0 & 0 & 1 \end{bmatrix}, \\
    w_{i, c} &= \begin{bmatrix} f_i \\
    \tau_i \end{bmatrix} = c_R w_{i, obj}.
\end{align*}
\]

By symmetry, it follows that \( \tau_{ix} = -\tau_{ix} \) and \( \tau_{iy} = -\tau_{iy} \) while \( \tau_{ix} = \tau_{ix} \) and \( \tau_{iy} = \tau_{iy} \) since the z-axis is unchanged. We also denote the actual wrench achieved by quadrotor \( i \) in the control frame by \( w_{i, c} = \)
Consider now, problem (17) for quadrotor j in the centrosymmetric pair (i, j). Thus \( d_j = d_i \), and \( \alpha_j = \alpha_i - \pi \). For quadrotor j, \( W^j_c \) has identical first and fourth rows as \( W^i_c \) as well as identical thrust and z-axes torque commands (i.e., \( \tau^j_{cz} = \tau^i_{cz} \), and \( f^j_z = f^i_z \)). The second constraint in (17) for quadrotor i reads as

\[
\tau^i_{cx} = r(C_{ai} - S_{ai})(f^i_z - f^i_z) + r(C_{ai} + S_{ai})(f^i_z - f^i_z),
\]

and for quadrotor j:

\[
\tau^j_{cx} = -\tau^i_{cx} = r(C_{aj} - S_{aj})(f^j_z - f^j_z) + r(C_{aj} + S_{aj})(f^j_z - f^j_z),
\]

where we leveraged the relation \( \alpha_j = \alpha_i - \pi \). The two equations above are equivalent, indicating that robot i and j have the same set of constraints when solving the optimization (17) in their respective local control frames. For the objective, notice that

\[
w^i(3) = d_i(f^i_z + f^i_z + f^i_z) + r(C_{ai} + S_{ai})(f^i_z - f^i_z),
\]

\[
w^j(3) = d_j(f^j_z + f^j_z + f^j_z) + r(C_{aj} + S_{aj})(f^j_z - f^j_z).
\]

Define the last two terms in (18), (19) as

\[
g(f^i) = r(C_{ai} + S_{ai})(f^i_z - f^i_z) + r(C_{ai} - S_{ai})(f^i_z - f^i_z),
\]

\[
g(f^j) = r(C_{aj} + S_{aj})(f^j_z - f^j_z) + r(C_{aj} - S_{aj})(f^j_z - f^j_z).
\]

Due to the identical constraints, \( g(f^i) \) and \( g(f^j) \) must have the same minimal and maximal value, denoted as

\[
p^\text{min} = \min g(f^i) = \min g(f^j),
\]

\[
p^\text{max} = \max g(f^i) = \max g(f^j),
\]

subject to the constraints in (17). Then according to (18), (19), (20), (21) and provided the feasibility set of (17) is non-empty, the optimal \( w^i(3) \) and \( w^j(3) \) for problem (17) are

\[
w^i(3)^* = \begin{cases} 
  d_i f^i_z + p^\text{min} & \text{if } \tau^{i}_{cy} \leq d_i f^i_z + p^\text{min} \\
  \tau^{i}_{cy} & \text{if } p^\text{min} < \tau^{i}_{cy} - d_i f^i_z \leq p^\text{max} \\
  d_i f^i_z + p^\text{max} & \text{else.}
\end{cases}
\]

\[
w^j(3)^* = \begin{cases} 
  d_j f^j_z - p^\text{max} & \text{if } \tau^{j}_{cy} \leq d_j f^j_z - p^\text{max} \\
  \tau^{j}_{cy} & \text{if } p^\text{min} < \tau^{j}_{cy} - d_j f^j_z \leq p^\text{min} \\
  d_j f^j_z + p^\text{min} & \text{else.}
\end{cases}
\]

These essentially describe two biased saturated curves, as shown in Figure 4. To characterize the combined y-axis torque output of the pair (i, j) under the strategy (17), we transform \( w^i(3) \), which is in j’s local frame, into i’s frame by reflecting and negating the curve for \( w^i(3) \). Then the total y-axis torque of pair (i, j), expressed in i’s frame is
\[ w' = (3)^{1/2} + w(3)^{1/2} = \begin{cases} 2p_{\min} & \text{if } \tau_{cy} \leq -d_i f_z^* + p_{\min}, \\ \tau_{cy} + d_i f_z^* + p_{\min} & \text{if } -d_i f_z^* + p_{\min} < \tau_{cy} < -d_i f_z^* + p_{\max}, \\ p_{\min} + p_{\max} & \text{if } -d_i f_z^* + p_{\min} \leq \tau_{cy} \leq d_i f_z^* + p_{\min}, \\ \tau_{cy} - d_i f_z^* + p_{\max} & \text{if } d_i f_z^* + p_{\min} < \tau_{cy} < d_i f_z^* + p_{\max}, \\ 2p_{\max} & \text{if } \tau_{cy} \geq d_i f_z^* + p_{\max}. \end{cases} \]

which is a piecewise linear function with respect to the requested wrench from the SE(3) controller, as visualized in Figure 4. Given these response curves, we present pairwise compensation technique to address the bias and deadband characteristics of each quadrotor in a given centro-symmetric pair.

C. Pairwise Torque Compensation

The output torque profile of (17) plotted in Figure 4 makes control challenging and stability analysis difficult. In this section, however, we show that under Assumption 1 the compensation can be done without communication such that the actual y-axis combined torque output of the (i,j) pair exactly replicates the desired SE(3) torque, as shown in the green dashed line in Figure 4.

Observe from (24) and Figure 4 that when

\[ p_{\min}^* + p_{\max}^* = 0, \]

the torque output profile becomes a symmetric deadband curve centered at the origin. Consequently, the capable quadrotor (defined as the quadrotor with positive requested y-axis torque in a given symmetric pair) can exert additional torque (beyond its original local command) to compensate for the offset from its complement in the symmetric pair. Mathematically, this process requires each quadrotor to solve two optimization problems. First, find \( p_{\min}^* \) and \( p_{\max}^* \) by solving (20) and (21). Denote

\[ p^* = \min\{|p_{\min}^*|, |p_{\max}^*|\}, \]

Choose \( p_{\min}^* = -p^* \) and \( p_{\max}^* = p^* \), thereby allowing the pair to satisfy condition (25). This means that both quadrotors \( i \) and \( j \) will choose their y-axis wrench within \( [d_i f_z^* - p^*, d_i f_z^* + p^*] \), which we know is feasible since it is a subset of original y-axis torque range as a result of (26). Second, we present the final wrench controller with compensation by.

Problem 1. (Distributed Wrench Controller) During the cooperative aerial manipulation task, each quadrotor’s motor thrusts are given by the solution of

\[
\begin{align*}
\text{minimize} & \quad |w'(3) - \tau_{cy}^i| \\
\text{subject to} & \quad \text{Constraints in (17),} \\
& \quad d_i f_z^* - p^* \leq w'(3) \leq d_i f_z^* + p^*,
\end{align*}
\]

where

\[ \tau_{cy}^i = \begin{cases} 2\tau_{cy}^i + d_i f_z^* - p^* & \text{if } \tau_{cy}^i \geq 0, \\ \tau_{cy}^i & \text{if } \tau_{cy}^i < 0. \end{cases} \]

In (28), \( \tau_{cy}^i \) is the adjusted torque along the local y-axis. Notice that the capable quadrotor compensates for the deadband and the offset torque created by the “incapable” quadrotor (i.e., quadrotor \( j \) in this notation); see Figure 4 for the (i,j) pair. Finally, note that all the computation here requires only local information such that the compensation can be done without communication.

D. Closed-Loop Stability

Given the pairwise compensation strategy presented in the preceding discussion, closed-loop stability is now a straightforward conclusion of the following proposition. For simplicity, assume all diagonal gain matrices are equal and given by \( k_p, k_v, k_R, k_w \).

Proposition 1 (Closed-Loop Stability). (i) Define the (positive-definite) attitude error function

\[ \Psi(R, R_{\text{des}}) := \frac{1}{2} \text{tr}[I - R_{\text{des}}^T R], \]

and, consistent with the assumptions for Proposition 3 in [2], suppose that (1) the initial errors satisfy the bounds:

\[ \|e_{\omega}(0)\| \leq \frac{2}{\lambda(J)} k_R (\psi_1 - \Psi(R(0), R_{\text{des}}(0))), \]

\[ \|e_{p}(0)\| < e_{p_{\max}}, \]

where \( e_{p_{\max}} > 0 \) is a design parameter and \( \lambda(\cdot) \) refers to the largest, respectively, smallest eigenvalues, and (2) define \( \gamma := \sqrt{\psi_1 (2 - \psi_1) < 1} \) and choose positive constants \( A_1, A_2 \) such that:

\[ A_1 < \min \left\{ k_v (1 - \gamma), \sqrt{k_p m}, \frac{4m k_w k_p (1 - \gamma)^2}{k^2_v (1 + \gamma)^2 + 4m k_p (1 - \gamma)} \right\}, \]

\[ A_2 < \min \left\{ k_w, \sqrt{k_R \lambda(J)}, \frac{4k_R k_p^2 \gamma^2 (J)}{k^2_w \lambda(J) + 4k_R \lambda^2(J)} \right\}. \]

(ii) Suppose problem (27) is feasible at every timestep with optimal value zero for the “capable” quadrotor and \( d_i f_z^* - p^* \) for the “incapable” quadrotor.

Then, the closed-loop equilibrium \( (e_p, e_v, e_R, e_{\omega}) \) for the object trajectory errors is exponentially stable.

Proof: The results follow from the stability of the SE(3) controller [2] and the fact that the compensation scheme given in (27) and (28) results in a total applied wrench equal to the wrench commanded by the SE(3) controller.

IV. ONLINE FEASIBILITY

As Proposition 1 states, closed-loop exponential stability is contingent upon both feasibility and optimality of (17) and (27). By symmetry of the desired thrust, and x- and z-axes torques for a given centro-symmetric pair, this is equivalent to the feasibility of the following problem for every capable quadrotor \( i \):

\[ \begin{align*}
0 \leq f^i & \leq f_{\max}, \\
W_i^c f^i & = w_{\tau_{cy}}^i,
\end{align*} \]

where \( w_{\tau_{cy}}^i = (f_{z^i}, \tau_{cy}^i, \tau_{cy}^i)^T \).
While the control law given in eqs. (7) and (8) does not give an a priori bound on the control input, in this section we derive conservative bounds for the initial trajectory errors and reference trajectory signals so that the problem above is always feasible. We will do this in two steps. First, we derive a bound on the SE(3) controller given in (7) and (8) as a function of the nominal trajectory and its derivatives, and the tracking errors. Next, we characterize the wrench output space of each quadrotor.

A. Bounding the SE(3) Controller

We begin by deducing bounds on all tracking errors, provided the stability conditions given in Proposition 1 are satisfied.

**Proposition 2** (Trajectory Tracking Bounding). Provided the assumptions of Proposition 1 hold, then

\[
\begin{align*}
||e_R(t)|| &\leq \sqrt{2\psi_1}, \quad \forall t \geq 0, \\
||e_\omega(t)|| &\leq \frac{1}{\sqrt{2k_1\psi_1}}, \quad \forall t \geq 0, \\
||e_p(t)||^2 + ||e_v(t)||^2 &\leq \frac{ke_{\max}^2}{2\psi_2(M_1)}, \quad \forall t \geq 0,
\end{align*}
\]

where \(M_1\) is the positive definite matrix given as

\[
M_1 := \frac{1}{2} \begin{pmatrix} k_p & -A_1 \\ -A_1 & m \end{pmatrix}.
\]

**Proof:** See Appendix I.

Having obtained bounds on all errors, we now bound the net SE(3) controller wrench. Let the nominal thrust of the trajectory, i.e., \(m||\tilde{\sigma} - g e_3||\) be bounded between \([b, B]\). Then, by Cauchy-Schwarz and triangle inequalities,

\[
\begin{align*}
\quad &-k_p||e_p|| - k_v||e_v|| \leq f_e \leq k_p||e_p|| + k_v||e_v|| + B.
\end{align*}
\]

The SE(3) control torque is bounded as

\[
\begin{align*}
||\tau|| &\leq k_\tau||e_R|| + k_\omega||e_\omega|| + \\
&+ \sqrt{\frac{X(J)(||\omega_{\text{des}}|| + ||e_\omega||)^2 + }{2\psi_1}} + \\
&+ \frac{\sqrt{X(J)(||\omega_{\text{des}}||^2 + ||\omega_{\text{des}}|| + ||\omega_{\text{des}}||)}}{2\psi_1},
\end{align*}
\]

where

\[
\begin{align*}
||\omega_{\text{des}}|| &\leq \frac{X(||e_p||, ||e_v||, m||\tilde{\sigma}||, B)}{b - k_p||e_p|| - k_v||e_v||}.
\end{align*}
\]

The expression for \(X\) and the derivation itself are detailed in appendix I. We now make the following simplifying assumption: while the desired angular acceleration \(\omega_{\text{des}}\) depends upon the second derivative of the unit vector \(-\tilde{F}_{\text{des}}/||\tilde{F}_{\text{des}}||\) which in itself involves terms related to jerk feedback, we approximate this term via its nominal value as derived from the differential flatness mapping (see, e.g., [4]) and assume that the relevant errors within \(\tilde{F}_{\text{des}}\) are negligible.

The control bounds in eqs. 33, 34, 35 are a function of tracking error bounds (Proposition 2), and the trajectory design parameters governing nominal thrust range \([b, B]\), jerk \(\tilde{\sigma}\), and angular acceleration \(\omega_{\text{des}}\). This allows us to conservatively bound the SE(3) wrench in the object reference frame. In the next subsection, we show how to isolate the most constrained quadrotor wrench output space.

B. Quadrotor Wrench Output Space

Consider problem (29) for any capable quadrotor \(i\) (i.e., \(\tau_{\text{cy}} > 0\)). In order for the quadrotor to achieve a y-axis torque equal to the adjusted value \(\tau_{\text{cy}}^{\ast}\), one requires \(w_{\text{cy}}^{\ast}\) to lie in the set:

\[
W_{\text{cy}}^{\ast} := \{w_{\text{cy}} \in \mathbb{R}^3 : W_{\text{cy}}^f = w_{\text{cy}}, \quad 0 \leq f \leq f_{\text{max}}\}.
\]

Given eq. (28), this requires \(\tau_{\text{cy}}^{\ast} \in [d_i f_{\text{y}}^i - p^*, d_i f_{\text{y}}^i + p^*] \iff \tau_{\text{cy}} \in [0, 2p^*]\). Thus, we deduce that the uncompensated, i.e., rotated 1/N wrench output from the SE(3) controller for each quadrotor must lie in the set:

\[
W_{\text{cy}}^i := \{w_{\text{cy}} : \dot{w}_{\text{cy}}^i \in W_{\text{cy}}^c\}
\]

(36)

where \(W_{\text{cy}}^c\) is the sub-matrix of \(W_{\text{cy}}^i\) excluding the third row and \(W_{\text{cy}}^c_{\text{y}}\) is a similarly defined sub-vector of \(W_{\text{cy}}^i\), and we have leveraged an absolute value constraint on \(\tau_{\text{cy}}\), since a negative \(\tau_{\text{cy}}\) simply implies that this is the incapable quadrotor and thus only the unbiased axes wrench commands are relevant. The set \(W_{\text{cy}}^i\) is referred to as the quadrotor wrench output space.

Note that the equality constraint on the unbiased wrenches in (36) describes a three-dimensional hyperplane within the four-dimensional hypercube of side length \(f_{\text{max}}\). For any given point on this hyperplane (i.e., given \(w_{\text{cy}}^c\)), the remaining wrench (y-axis torque) may be visualized as a vector stemming from this point with direction orthogonal to the hyperplane and magnitude constrained by \(p^*(\dot{w}_{\text{cy}}^i)\).

In the following lemma, we establish that this inequality constraint may be captured using affine inequalities in \(w_{\text{cy}}^c\), thereby proving convexity of \(W_{\text{cy}}^i\).

**Lemma 1** (Convexity of \(W_{\text{cy}}^i\)). The set \(W_{\text{cy}}^i\) is convex and the constraint on \(|\dot{w}_{\text{cy}}^i(3)|\) can be captured using a set of affine inequalities in \(w_{\text{cy}}^c\).

**Proof:** See Appendix II.

The given result above along with Euclidean bounds on net SE(3) control thrust and torque (which can be rotated without change into the local control frames due to length invariance of \(2\mathbb{R}\)), checking closed-loop control feasibility reduces to verifying whether or not a set of the form \(f_{\text{z}}/N \in [\varepsilon f_{\text{z}}, \pi f_{\text{z}}]\), \(|\tau||/N \leq \varepsilon, f_{\text{z}} \in W_{\text{cy}}^i\) for all \(i = 1, \ldots, N\).

V. Trajectory Planning Under Input Constraints

In this section we design the reference trajectory \(\sigma(t)\) by optimizing suitable objective functions, constrained by the requirement that the expected closed loop SE(3) wrench commands, conservatively bounded in Section IV-A, lie within the smallest quadrotor output wrench space, as characterized in Section IV-B.

We begin with a series of \(n + 1\) specified waypoints, \(\{P_i \in \mathbb{R}^3\}, \ i \in \{1, 2, \ldots, n + 1\}\), for 3D position, obtained using, for instance, a sampling-based planner [21]. The traversal times between waypoints are unspecified, and will
be automatically determined by the trajectory optimization. Each trajectory segment is represented by a polynomial,
\begin{equation}
\sigma_i(t_i) = \sum_{j=0}^{L} a_{ij} t_i^j, \quad 0 \leq t_i \leq T_i, \quad i \in \{1, \cdots, n\}
\end{equation}
where \(L\) is the order of the polynomial, \(a_{ij} \in \mathbb{R}^{4 \times 1}\) are the coefficients, \(t_i\) is the time within each section, and \(T_i\) is the duration of the \(i\)-th section.

Our goal is to minimize both the total time and the integration of snap squared under the input constraints. This is a challenging multi-objective optimization, whose variants are also considered in [20], [19], [22] for quadrotor planning. Notably however, the formulation in [20] only accounts for thrust constraints while [19], [22] bound thrust and angular rates. Neither of these works also consider expected closed-thrust constraints while [19], [22] bound thrust and angular rates. Notably however, the formulation in [20] only accounts for

A. Snap Minimization with Fixed Duration

We first consider the subproblem where we only minimize the integral of snap, assuming given section duration times \(\{T_i\}\) and neglecting input constraints. The formulation here corresponds to the one presented in [20], however, it is included here for self-containment. Formally, we solve:

\begin{align*}
\minimize & \sum_{i=1}^{n} \int_{0}^{T_i} (\dddot{\sigma}_i)^2 dt_i \\
\subjectto & \sigma_i(0) = P_i, \quad i \in \{1, \cdots, n\} \\
& \sigma_i(T_i) = P_{i+1}, \quad i \in \{1, \cdots, n\} \\
& \frac{d^r \sigma_i}{dt^r_i} \bigg|_{t_i=0} = \frac{d^r \sigma_{i+1}}{dt^r_{i+1}} \bigg|_{t_{i+1}=0}, \quad r \in \{1, \cdots, 5\}, i \in \{1, \cdots, n-1\}, \\
& \frac{d^q \sigma_1}{dt^q_1} \bigg|_{t_1=0} = \frac{d^q \sigma_n}{dt^q_n} \bigg|_{t_n=T_n} = 0, \quad q \in \{1, \cdots, 4\}.
\end{align*}

(38)

where the decision variables are \(\{a_{ij}\}\). The first two constraints in (38) ensure that the trajectory passes through all given waypoints. The third constraint enforces continuity on all derivatives up to fifth order. The last constraint specifies initial and final velocity, acceleration, jerk, and snap, which are all zero in our case. Using the parameterization in (37), the objective has an analytical quadratic form in the polynomial coefficients \(a_{ij}\). Furthermore, all constraints are affine in \(\{a_{ij}\}\). Thus, (38) is a QP and can be solved efficiently. Moreover, the four dimensions of \(\sigma\) are decoupled so that (38) can be solved independently for each dimension.

B. Coordinate Descent on Section Duration under Input Constraints

We now consider the section duration times and the input constraints by solving the following higher-level optimization problem:

\begin{align*}
\minimize & \sum_{i=1}^{n} T_i \\
\subjectto & T_i \geq 0, \\
& \mathbf{w}_{\text{obj}}(\sigma, \dddot{\sigma}, \dddot{\sigma})/\mathbf{N} \in \mathcal{W}_i^N, \quad \forall i = 1, \cdots, N, 
\end{align*}

over the set of duration times \(\{T_i\}\), where \(\sigma\) is the solution of the snap minimization subproblem. Note that the wrench expression considered in (39) corresponds to the closed-loop bounds derived in Section 4.1, and are therefore, implicitly parametric in the tracking error bounds (Proposition 2), as well as explicitly dependent upon the derivatives of \(\sigma\). Due to the complexity of these bounds, we leverage an exterior point method using penalty functions, and evaluate the input constraints numerically, as described in Section 4.2 by traversing the entire trajectory. Note that by ignoring closed-loop effects and only leveraging the open-loop control signal, the constraint verification reduces to checking the inclusion of a single point within the sets \(\{\mathcal{W}_i^N\}\), instead of the set \(\{f_z/\mathbf{N} \in [\varepsilon_{f_z}, \tau_{f_z}], \|\tau\|/\mathbf{N} \leq \varepsilon_r\}\).

To solve the optimization, we use a gradient-free coordinate descent algorithm and perform line search along each dimension. Coordinate descent has the advantage of avoiding ill-conditioned gradients which may arise, for example due to the input constraints, or by adding penalty functions to the cost itself.

The overall solution to (39) is detailed in Algorithm 1. In line 13 we evaluate the penalty due to the worst case violation of control bounds along the trajectory using \(\delta\), a measure of the amount of violation. In line 16 we use the golden section search to perform the one-dimension line search on the interval \([0, T_{\text{max}}]\), where \(T_{\text{max}}\) is given and large enough. Also, when doing line search on the \(i\)-th dimension, we fix \(T_j\) for \(\forall j \neq i\) and only vary \(T_i\). The entire algorithm thus finds a locally optimal duration set in an iterative fashion.

Remark 1. An important observation here is that the problem in (39) is always feasible by selecting \(T_i\) to be sufficiently large and initial tracking errors sufficiently small. Then, since the QP subproblem can be solved extremely quickly (indeed, analytically using the method given in [20]), the full bi-level optimization algorithm may be run in anytime fashion with solution quality only being a function of online computational time limits.

An example result of Algorithm 1 is shown in Figures 5, 6 and 7 where we are given six waypoints, and control inputs were verified using a single fixed size inner approximation to the quadrotor wrench output spaces, namely: \(\varepsilon_{f_z} = (m g - 0.5)/\mathbf{N}, \tau_{f_z} = (m g + 0.5)/\mathbf{N}, \varepsilon_r = 0.01/\mathbf{N}\). As can be seen in the figures, the reference thrust and moments using the full optimization stay within the selected bounds at all times.
Algorithm 1: Trajectory Optimization with Input Constraints

1: \( T_i \leftarrow T_{\text{max}}, \forall i \in \{1, \ldots, n\} \)
2: \( r = 1 \)
3: \textbf{while not converged} \textbf{do} 
4: \quad \textbf{for} \( i = 1 \) to \( n \) \textbf{do} 
5: \quad \quad \( T_i \leftarrow \text{LINESEARCH}(i, T, r) \)
6: \quad \textbf{end for} 
7: \quad \( r \leftarrow 10 \times r \)
8: \textbf{end while} 
9: \quad \textbf{return} \( T \)
10: \quad \textbf{function} \text{LINESEARCH}(i, T, r) 
11: \quad \quad // Construct objective function 
12: \quad \quad \sigma(T) \leftarrow \text{Solve (Snap Minimization)}
13: \quad \quad P(T) = \max(\max(\delta(\sigma)), 0) \)
14: \quad \quad f(T) = \sum_{i=1}^{n} T_i + r P(T) \)
15: \quad // Line search on \( i \)-th dimension 
16: \quad \quad T_i \leftarrow \text{GoldenSectionSearch}(f, T, i, [0, T_{\text{max}}])
17: \quad \textbf{return} \( T_i \)
18: \textbf{end function}

Fig. 5. Trajectory comparison between using only snap minimization with handpick section duration (dashed line) and the full optimization with input constraints \( \sigma \) (solid line).

VI. Simulation

In this section we present simulation studies validating the proposed distributed control algorithms. The snapshots of our case study is shown in Figure 8. Eight symmetrically placed quadrotors are used to lift an object and traverse a complex 3D environment, where the straight line path to the destination is blocked and numerous 3D maneuvers must be performed to avoid colliding with obstacles. This simulates a disaster relief scenario where the highly unstructured space is difficult to navigate for humans and ground robots. The quadrotor-object assembly weighs 2kg, with moment of inertia 0.17kg·m² along \( x \), \( y \) axis and 0.34kg·m² along the \( z \) axis. Each quadrotor has a small footprint with maximum thrust capability \( f_{\text{max}} = 0.9N \) per rotor; therefore at least 6 quadrotors are needed to balance gravity. We solved the path planning problem using sampling based techniques \cite{1} and leveraged bounding convex bodies for collision checking, and fed the waypoints into Algorithm 1 to generate the reference trajectory. During the simulation, each quadrotor independently computes its control inputs using (27) given the trajectory broadcast, without any information from other quadrotors. As shown in Figure 8 the quadrotors successfully transport the object to the destination while tightly following the reference trajectory. The position tracking performance and Euler angles of the object are plotted in Figure 9.

To further demonstrate the applicability and robustness of our approach, we also performed several additional simulations by adding the following challenges: (i) Independent zero-mean Gaussian noise is applied to the sensors on all the quadrotors. (ii) The attachment points of the quadrotors are perturbed within a 0.1m radius around their nominal location on the object (which is 0.5m away from the center of mass of the object), thereby violating the centro-symmetry condition. (iii) Initial tracking errors up to 0.15m are introduced. Despite these various sources of error, results suggest that the assembly can still achieve high quality tracking performance comparable to the performance in Figure 9. As a comparison with the noise free case, we plot the magnitude of position \( \|e_p\| \) and attitude \( \|e_R\| \) errors in Figures 10 and 11 respectively. We find that the noisy case still satisfies reasonable bounds on the error signal, verifying the practicality of our approach under disturbances. We also provide videos of both simulations in the supplemental material.

VII. Conclusion and Future Work

In this work we presented a distributed algorithm to transport heavy objects using a fleet of rigidly attached aerial robots with no peer communication. Under the mild centro-symmetric assumption, we rigorously analyzed pairwise controllability and derived a compensation scheme to guarantee collective group control authority and ensure stable tracking behavior. The feasibility of the algorithm is ensured by bounding the expected closed-loop control usage, characterizing the wrench capabilities of each quadrotor in the assembly, and explicitly enforcing these constraints along the time- and snap-optimized trajectory. The algorithms were thoroughly tested in simulation and shown to be resilient to sensor noise and violation of the geometric assumption.
We provide several avenues for future investigation. In particular, we wish to investigate online adaptation techniques to (1) permit relaxing the centrosymmetry condition, and (2) design more effective control allocation techniques. In addition, we plan to validate our algorithms on a hardware test bed for a range of lifting scenarios and quadrotor configurations.

REFERENCES


**APPENDIX I**

### SE(3) CONTROL WRENCH BOUNDS

**Proof:** [Proof of Proposition 2] Provided the conditions stated in the proposition above hold, Prop. 3 in [2] establishes the following conclusions: First,

\[ \Psi(R(t), R_{\text{des}}(t)) \leq \psi_1 \quad \forall t \geq 0, \quad (40) \]

i.e., the attitude error, represented by the rotation matrix \( R_{\text{des}}^T R \) is less than 90° for all time. Second, the function

\[ V_R := \frac{1}{2} ||e_\omega||_2^2 + k_R \Psi(R, R_{\text{des}}), \quad (41) \]

is non-increasing, and third, the function

\[ V := ||z_1||^2_{M_1} + ||z_2||^2_{M_2}, \quad (42) \]

where \( z_1 := (||e_p||, ||e_v||)^T, z_2 := (||e_R||, ||e_\omega||)^T, \) and \( M_2 \) is a strictly positive definite matrix, is bounded above by \((1/2)k_p r_{\text{max}}^2\) for all \( t \geq 0 \). The matrix \( M_2 \) is defined as:

\[ M_2 := \frac{1}{2} \left( \begin{array}{cc} k_R & -A_2 \\ A_2 & \Delta \end{array} \right). \]

As a consequence of (40), write \( R_{\text{des}}^T R = \exp(\beta \nu) \), where \( \beta \in [0, \pi/2) \) and \( \nu \in S^2 \). By Rodrigues’ formula, \( ||e_R|| = |\sin \beta| = \sin \beta \) and \( \Psi(R, R_{\text{des}}) = 1 - \cos \beta \leq \psi_1 < 1 \). The bound (39) follows immediately. Equations (31) and (32) also follow straightforwardly from (41) and (42).

We now bound the net SE(3) control torque. Re-writing \( \omega \) as \( e_\omega + R^T R_{\text{des}} \omega_{\text{des}} \), we obtain \( \dot{\omega} R^T R_{\text{des}} \omega_{\text{des}} = \dot{e}_\omega R^T R_{\text{des}} \omega_{\text{des}} \) which is simply the cross product of \( e_\omega \) (defined in the current object body frame) and the projection of \( \omega_{\text{des}} \) into the current body frame. Thus, we obtain

\[ ||\dot{\omega} R^T R_{\text{des}} \omega_{\text{des}}|| = ||e_\omega|| ||\omega_{\text{des}}||. \]

Finally, \( ||\dot{\omega} J \omega|| \) is trivially bounded above by

\[ \sqrt{\lambda(J)} (||\omega_{\text{des}}|| + ||e_\omega||)^2. \]

Thus, the net desired torque is bounded by

\[ ||\tau|| \leq k_R ||e_R|| + k_v ||e_v|| + \sqrt{\lambda(J)} (||\omega_{\text{des}}|| + ||e_\omega||)^2 + \sqrt{\lambda(J)} (||e_\omega|| ||\omega_{\text{des}}|| + ||\omega_{\text{des}}||). \]

To obtain a bound on \( \omega_{\text{des}} \), note that

\[ \begin{pmatrix} \omega_{\text{des}}^T \\ -\omega_{\text{des}} \end{pmatrix} = R_{\text{des}}^T \left( \frac{F_{\text{des}} F_{\text{des}}^T}{||F_{\text{des}}||^2} - I \right) \dot{F}_{\text{des}} \]

which is simply the orthogonal projection of \( \dot{F}_{\text{des}}/||F_{\text{des}}|| \) onto the plane with normal \( F_{\text{des}}/||F_{\text{des}}|| \) [22]. Furthermore, by appropriately choosing \( \sigma_\psi \) (and via integration, \( \sigma_\psi \)) online, we constrain \( \omega_{\text{des}} \) at 0. Then,

\[ ||\omega_{\text{des}}|| \leq \frac{||F_{\text{des}}||}{||F_{\text{des}}||} \]

\[ \leq \frac{k_p e_v + k_v e_v + m \dot{\alpha}}{b - k_p ||e_p|| - k_v ||e_v||} \]

\[ \leq b - k_p ||e_p|| - k_v ||e_v|| \]

where the last inequality follows from bounding \( \dot{e}_v \) whose expression is derived in [2], and

\[ X = k_p k_v (\gamma + \frac{1}{m}) ||e_p|| + \left( \frac{k_p - k_v}{m} \right) ||e_v|| + m \frac{\dot{\alpha}}{\gamma} \frac{k_v}{k_v} B. \]

**APPENDIX II**

### CONVEXITY OF WRENCH OUTPUT SET

**Proof:** [Proof of Lemma 1] Consider any two elements \( \hat{w}_i \in W_c \) and let \( \hat{w}_i := \beta \hat{w}_i^c + (1 - \beta)\hat{w}_i^c \), where \( \beta \in [0, 1] \). Then, any element \( \hat{f} \) in the set \( \mathcal{F} := \{ \hat{f} \leq f_{\text{max}} : \hat{w}_i^c \hat{f} = \hat{w}_i^c \} \) is simply given by \( \beta \hat{f} + (1 - \beta)\hat{f} \), where \( \hat{f} \in \mathcal{F} := \{ \hat{f} \leq f_{\text{max}} : \hat{w}_i^c \hat{f} = \hat{w}_i^c \} \), and \( \hat{f} \in \mathcal{F} := \{ \hat{f} \leq f_{\text{max}} : \hat{w}_i^c \hat{f} = \hat{w}_i^c \} \).

Now, notice that the constraint on \( |\hat{w}_i^c(3)| \) may be written as

\[ |\hat{w}_i^c(3)| \leq -2 \min_{\hat{f} \in \mathcal{F}} \beta \hat{f}^c(3), \quad \text{and} \quad |\hat{w}_i^c(3)| \leq 2 \max_{\hat{f} \in \mathcal{F}} \hat{f}^c(3). \]

Similarly

\[ |\hat{w}_i^c(3)| \leq -2 \min_{\hat{f} \in \mathcal{F}} \hat{f}^c(3), \quad \text{and} \quad |\hat{w}_i^c(3)| \leq 2 \max_{\hat{f} \in \mathcal{F}} \hat{f}^c(3). \]

Thus, by triangle inequality,

\[ |\hat{w}_i^c(3)| \leq \beta |\hat{w}_i^c(3)| + (1 - \beta) |\hat{w}_i^c(3)| \]

\[ \leq -2 \min_{\hat{f} \in \mathcal{F}} \beta \hat{f}^c(3) - 2(1 - \beta) \min_{\hat{f} \in \mathcal{F}} \hat{f}^c(3) \]

\[ = -2 \min_{\hat{f} \in \mathcal{F}, \hat{f} \in \mathcal{F}} \left( \beta \hat{f}^c(3) + (1 - \beta)\hat{f}^c(3) \right) \]

\[ = -2 \min_{\hat{f} \in \mathcal{F}} \beta \hat{f}^c + (1 - \beta)\hat{f}^c \]

\[ = -2 \min_{\hat{f} \in \mathcal{F}} \hat{f}^c = 2 p_{\text{max}}(\hat{w}_i^c). \]

where the second-to-last equality follows by linearity of \( g(\hat{f}) \) in \( \hat{f} \). Similarly, it follows that

\[ |\hat{w}_i^c(3)| \leq 2 \max_{\hat{f} \in \mathcal{F}} \hat{f}^c = 2 p_{\text{max}}(\hat{w}_i^c). \]
Thus, $w_i^t$ lies in $W_i^t$, proving convexity, and $|p_{\text{min}}^*|$ and $p_{\text{max}}^*$ are affine in $w_{e-s}^t$. 