Dynamically Feasible and Safe Shape Transitions for Teams of Aerial Robots

Arjav Desai, Ellen A. Cappo, and Nathan Michael

Abstract— We consider the problem of generating dynamically feasible and safe plans for teams of aerial robots (quadrotors) while holding a fixed relative formation as well as transitioning between a sequence of formations. We extend the existing assignment and planning approaches for quadrotor teams to find minimal-time trajectories to enable team transition between non-rest initial and ending states while ensuring dynamic feasibility with respect to predefined kinematic, dynamic, and collision constraints. This work also presents a method for safe splitting and merging of robot formations according to input specification. The proposed methodology is capable of generating dynamically feasible and safe plans for teams of quadrotors in real time. We validate the performance of the proposed approach through various trials and scenarios conducted in simulation.

I. INTRODUCTION

We are interested in the coordination and control of large teams of micro air vehicles as a means of visual narration in an unscripted theatrical production. A performer (operator) articulates the desired team behavior online through gestures that are interpreted as the specification of desired individual and collective behaviors and transformed into coordination and control strategies executed by the robot team including: formation control based on virtual rigid structures [6, 16], shape transitions and variations [20, 21], and formation and shape splitting and merging. In this work, the problem of developing dynamically feasible and safe transitions between behaviors in response to and based on the input from the performer is considered. Figure 1 depicts a representative scenario where the operator requests that the robots transition between multiple shapes, splitting and merging formations while moving through the performance workspace.

A key requirement of this application is the preservation of the aesthetic appeal and visual connection (by the audience) between the operator input (gestures) and team response, both temporally and behaviorally. Therefore, we propose a formulation that can respond to requests in real-time with corresponding behaviors that are time-optimal (visually appealing) while preserving dynamic feasibility and safety. As the performer generates inputs, the inputs are transformed into a set of requested behaviors. Each collective behavior corresponds to a shape and ensemble motion specification based on the techniques proposed in our prior work [18, 19]. The resulting behaviors enable coordination of the ensemble in the form of a class of shapes (e.g., triangle and square) that vary in structure and form based on the number of requested

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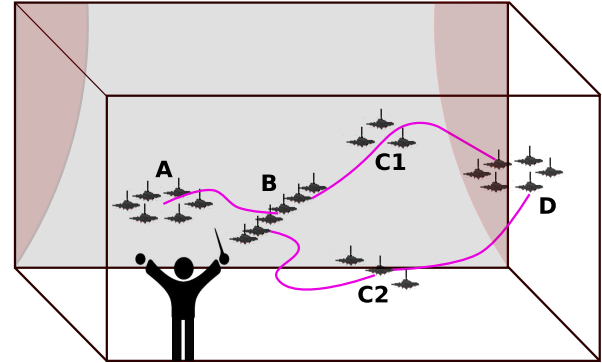
Fig. 1: A team of quadrotors respond to input from a performer in an unscripted theatrical performances. The performer instructs the team of six robots to engage in behaviors including: transition to a circular formation (**A**), transition into a line formation (**B**), split into two smaller formations (**C1, C2**), and finally merge together into a circular formation (**D**).

robots and ensemble behavior. The transition between shapes in response to performer input is formulated as a goal assignment problem (Sect. II) and corresponding optimal trajectories are computed as depicted in Fig. 1 given a transition from **A** to **B**. Splitting and merging of shapes is similarly formulated as a goal assignment problem (Sect. II-E) and depicted in Fig. 1 as a transition from **B** to **C1** and **C2**.

The proposed methodology builds on techniques related to time optimal trajectory generation and feasibility verification with respect to kinodynamic constraints as well as prior work in the areas of multi-robot formation control and ensemble splitting and merging. Rich literature exists in the area of time optimal motion planning in the context of motion planning for industrial manipulators including *bang-bang* strategies that fulfill the necessary conditions set by the Pontryagin's minimum principle [4]. These methods are recently extended to quadrotor systems in order to generate time optimal trajectories [8, 9, 11, 14]. A challenge in these formulations is the online computation time required to solve for an optimal motion plan, thereby limiting their viability in our application context. In this work, the trajectory generation method proposed by Richter et al. [15] is leveraged to generate optimal trajectories by solving an unconstrained quadratic program to yield an initial trajectory assuming a conservative time-scale. The trajectory time-scale is further refined through application of the bisection method to find candidate end times [7, 15] that ensure dynamic feasibility given actuator constraints and the differentially flat quadrotor

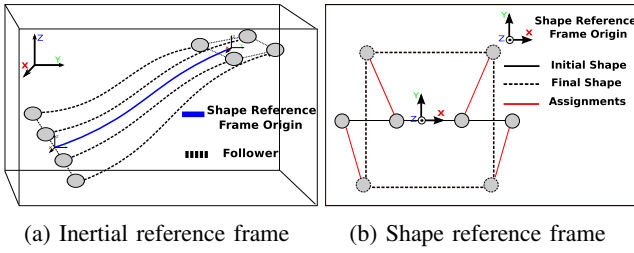(a) Inertial reference frame (b) Shape reference frame

Fig. 2: Four robots in a formation transition from a line to a square formation in the inertial and shape reference frames (Figs. 2a and 2b, respectively). The blue and black dotted curves depict the trajectory of the shape reference frame origin and the individual robot trajectories, respectively.

model [3]. The proposed formulation seeks to balance low computation times with near-optimal trajectory generation for teams of robots.

While the proposed formulation ensures dynamic feasibility through time-scaling (given the differentially flat vehicle model), inter-robot collision avoidance during shape transitions as well as the ensemble splitting and merging behaviors must also be ensured. Methods proposed in the literature to this end include vector field-based formulations [20, 21], optimization-based techniques (where safety requirements are encoded as collision constraints) including MIQP [13] and SCP [1, 2] formulations, as well as task allocation-based approaches [18, 19]. In this work, we build on our prior work [19] by leveraging robot prioritization and trajectory time-scaling to avoid collisions given conflicting trajectories. Validation is done through simulation trials and corresponding performance evaluation (Sect. III) to show that the proposed methodology is a viable online strategy to achieve the intended objective of dynamically feasible and safe shape transitions for teams of aerial robots.

II. SHAPE SPACE FORMULATION AND TRANSITIONS

We seek to find minimal time, feasible, and collision free transitions between formation shapes for a group of robots based on input from an operator in the form of a behavior specification that encodes the enumeration of robots and desired formation shape as well as the desired motion of the formation (e.g., from location **A** to **B**) and rate of motion (e.g., slow or fast). The methodology is decomposed into four steps:
1) *Shape specification* given the desired starting and ending configurations;
2) *Optimal assignment* given the initial and final shape reference configurations and current system state;
3) *Feasible trajectory generation* given the robot assignments, robot actuator constraints, and requested shape reference trajectory; and
4) *Collision checking and relative time scaling* to ensure near time optimal trajectories that respect the required safety constraints.

In this work, our shape transition approach is developed for planar formations including two dimensional regular
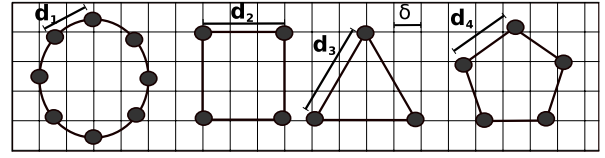

Fig. 3: Representative planar regular geometric formations considered in this work. Each edge of the grid represents the minimum safe distance between the centers of any two robots in the formation (δ) with, $\delta < d_1 < d_2 < d_3 < d_4$.

geometric shapes such as lines, circles, and polygons with representative formations for teams of varying size (Fig. 3). The robots are assumed to be homogeneous and interchangeable with no specific preference to goal locations. The extents of each robot is defined by a set of points confined to a ball, $\mathcal{B}_r$, of radius r. Further, the region $\mathcal{K}$, defined by the convex hull of the source and goal locations, is assumed obstacle free with the robot start and goal positions located δ distance apart, where δ is the predefined minimum safe distance. Finally, perfect state knowledge is assumed with no errors in actuation.

A. Shape Specification and Transitions

Following Turpin et al. [17], we define a *shape* as the specification of relative states between robots with respect to a reference frame. Figure 2 illustrates a shape specification for two formations consisting of four robots, depicted with respect to a single shape reference frame. A shape is defined as a time varying shape vector, $s(t)$, that encodes the relative pose between pairs of robots in the formation, and between every robot and the origin of the local shape reference frame. For convenience, a *leader* robot (potentially virtual) is always aligned with the local origin. A trajectory for the shape is defined such that the shape reference frame moves relative to the inertial frame. A shape vector for the ith and j^{th} robots is defined based on the relative position and heading of the two robots in $\mathbb{R}^3 \times \mathbb{SO}(2)$:

$$\mathbf{s}_{i,j}(t) = \mathbf{x}_j(t) - \mathbf{x}_i(t) = \begin{bmatrix} x_j(t) - x_i(t) \\ y_j(t) - y_i(t) \\ z_j(t) - z_i(t) \\ \psi_j(t) - \psi_i(t) \end{bmatrix} \quad (1)$$

with the properties:

$$\begin{aligned} \mathbf{s}_{i,k} &= \mathbf{s}_{i,j} + \mathbf{s}_{j,k}, \quad \forall i,j,k \in \{1,\dots,N\} \\ \mathbf{s}_{i,i} &= [0\ 0\ 0\ 0]^{\text{T}} \\ \mathbf{s}_{i,j} &= -\mathbf{s}_{j,i} \end{aligned} \quad (2)$$

where dependence on t is dropped for convenience.

A single ensemble trajectory is defined by transforming the shape reference frame relative to the inertial frame. $C(t)$ is a time-varying polynomial trajectory that encodes the position of the shape reference frame in the inertial frame and the time-varying rotation matrix describing the group's rotation in the inertial frame, $R(t)$. The inertial-frame single robot trajectory, $\gamma_i(t)$, is computed by

$$\gamma_i(t) = C(t) + R(t)s_i(t) \quad (3)$$

where $s_i(t)$ is defined according to (1) relative to the shape reference frame. The origin associated with each shape geometry is chosen as the mean of the associated robot positions with the start and goal shape configurations specified accordingly.

We define the optimal shape transition trajectory generation problem as one of computing time-optimal trajectories that enable a team of robots to transition from one shape trajectory to another shape trajectory. The techniques proposed by Turpin et al. [17] extend immediately to shape transitions given the same number of robots (e.g., the transition detailed in Fig. 2) through an appropriate specification of the ensemble shape trajectory. However, in this work, we wish to allow transitions between shapes requiring different enumerations. For this reason, we choose to distinguish between behaviors based on shapes and formulate shape transition trajectories.

Given the above formulation and operator input, an optimal shape transition trajectory is computed based on the current system state and the desired formation enumeration and shape. The transition trajectory is formulated as above and computed based on the optimal trajectory generation techniques proposed by Richter et al. [15] assuming a conservative trajectory time duration, t_f, that corresponds to the current and requested ensemble rates of motion. The resulting shape trajectory and corresponding robot trajectories lead to the expected traversal time costs given the current and desired shape configuration that enables time-optimal assignment of robots to the shape configuration specification.

B. Optimal Goal Assignment

Shape transitions are formulated as an optimal assignment of robots to desired goals in the shape reference frame (as depicted in Fig. 2b) that seek to minimize the associated traversal time costs. The optimal assignment is computed based on methods detailed in our prior work [19] and seeks to minimize the p-norm of the costs incurred by the team in order to reach the goal configuration

$$\phi^* = \arg \min_\phi \left(\sum_{i \in I_N} ||P(s_i, g_{\phi_i})||^p \right)^{\frac{1}{p}} \quad (4)$$

where I_N is the index set of the robots in the group and s_i and g_{ϕ_i} correspond to the initial and optimally assigned goal configurations of the ith robot, respectively. In this work, we choose to minimize the total distance traveled by the robots and thus let $p = 2$. The optimal assignment is computed via the Hungarian algorithm with $O(N^3)$ computational complexity [10].

C. Ensuring Rapid and Feasible Shape Transitions

The optimal shape trajectory and robot assignments detailed in Sects. II-A and II-B lead to the computation of desired individual robot trajectories (3) to be executed by the team of robots in order to transition between shapes. However, prior to transmitting the desired trajectory to each robot, we must ensure that the each trajectory does not require motions that exceed platform actuator constraints. To this end, we compute the maximum mass normalized
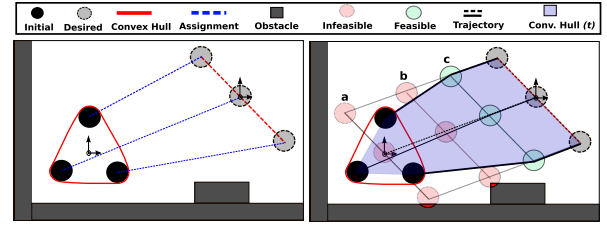

Fig. 4: Feasible and safe trajectory generation. Shape transition trajectory **a** is infeasible due to an acceleration constraint violation while trajectory **b**, although feasible, is not safe. Trajectory **c** is selected as it is both feasible and safe.

thrusts required by each trajectory, γ_i, based on the model and techniques proposed by Chamseddine et al. [3] and scale the shape transition trajectory duration, t_f, accordingly so as to ensure feasibility for all systems.

Alternatively, for visual appeal it is preferable that the robots rapidly transition between shapes. Therefore, if the resulting transition trajectories are overly conservative, we pursue a minimum transition time to enable rapid and feasible shape transitions:

$$\begin{aligned} \text{minimize} \quad & t_f \\ \text{subject to} \quad & -T_{max} \leq \ddot{\gamma}(t) \leq T_{max} \end{aligned} \quad (5)$$

with $t \in [0, t_f]$ (assuming without loss of generality that $t_0 = 0$), T_{max} is the maximum allowable mass normalized thrust, and

$$\ddot{\gamma}(t) = \ddot{R}(t)s(t) + 2\dot{R}(t)\dot{s}(t) + R(t)\ddot{s}(t) + \ddot{C}(t) \quad (6)$$

This minimization problem is solved online via a bisection line search [5], computing the corresponding acceleration time-scale for each candidate time, t_{fs}, and update the trajectory duration upon termination ($t_f \leftarrow t_{fs}$).

A final consideration when computing and validating t_{fs} is highlighted by Fig. 4. As we seek the minimum time transition trajectory connecting the current shape trajectory to a desired shape trajectory, updating t_{fs} will lead to the same goal shape configuration but with a transition at a potentially different point along the goal shape trajectory. Consequently, this change can lead to collision scenarios that are deemed infeasible and are rejected accordingly.

D. Final Collision Checking and Time Scaling

Given a minimum time transition for all robots, we perform a safety check to ensure that all trajectories preserve a minimum separation distance between robots. If a minimum separation distance is not preserved, we apply prioritization and time-scaling techniques [19] according to an assigned ordering derived from the robot start and goal positions with respect to the shape specification.

Given the prioritization order, each robot trajectory is checked for collisions against trajectories of higher priority robots. In the event that a collision occurs between robots, we assign the trajectory of the lower priority robot a small, positive time offset to avoid collision with the robot of higher priority. This process is repeated iteratively until no collisions
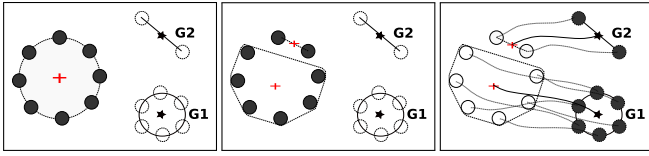
Fig. 5: Safe group splitting is decomposed into two steps including assignment and trajectory generation.

exist between the given robot and all higher priority robots. This results in collision free trajectories for all of the robots in the formation relative to the minimum transition time of the highest priority robot.

E. Group Splitting and Merging

The proposed formulation extends readily to group splitting and merging via the previously detailed techniques. Given a shape with N robots, we wish to split the formation into k shapes (requiring in total the same number of robots) via transition trajectories that are both safe and feasible. The definition of a merge is simply the converse of the split. A shape split or merge requires two steps (Fig. 5): (1) robot enumerations are computed by the assignment techniques of Sect. II-B and (2) safe and feasible shape trajectories are computed in the same manner as previously discussed for each of the k shapes. Inter-shape collision avoidance is readily incorporated into the second step by introducing an additional shape collision check against previously planned shapes.

III. SIMULATION EVALUATION

The assessment of the performance of the proposed planning approach is presented in Sects. II–II-E through simulation studies that evaluate performance given a large number of anticipated scenarios and operating conditions. To evaluate the performance and viability of the proposed methodology in the context of the unscripted theatrical performance application, we check the following five criteria: dynamic feasibility, safety, computation time, repeatability, and generalizability. The first three criteria are detailed through the prior discussion. The remaining criteria seek to ensure that as the performer requests diverse transitions, the planner will be able to generalize to the broad class of requested transitions with consistent performance.

We evaluate three metrics associated with the above criterion: maximum acceleration, minimum clearance distance, and instruction computation time. In this work, maximum body acceleration is used as a criteria for evaluating the dynamic feasibility requirement. The limit on maximum permissible acceleration is set to $8.6\,\mathrm{m/s^2}$ and based on the physical constraints of the application systems. Trajectories that violate this limit are considered infeasible. Clearance distance between robot centers serves as a measure of trajectory safety with a minimum safety distance of $0.5\,\mathrm{m}$ in this work. Trajectories are deemed unsafe if the minimum clearance distance between robot centers drops below this threshold. Finally, the time required to generate trajectories is considered. The average instruction computation time as
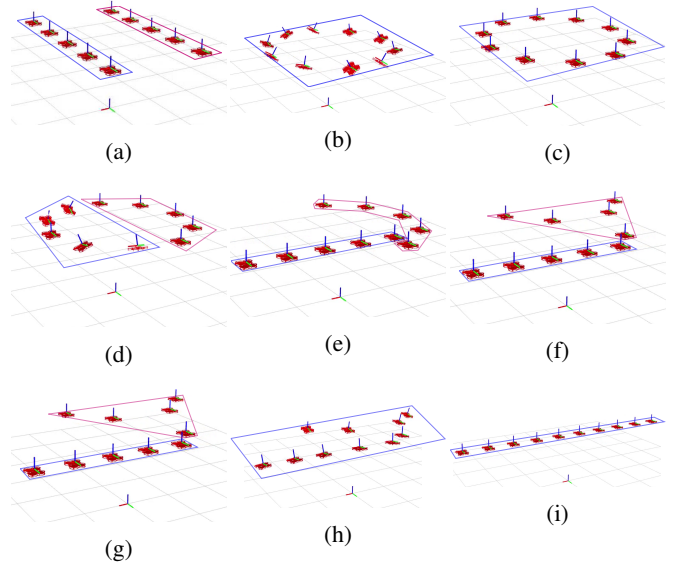

Fig. 6: Snapshots of shape transitions (Figs. 6a - 6c), splitting (Figs. 6d - 6f) and merging (Figs. 6g - 6i) of robot formations from experiments conducted for 10 robots in a high fidelity simulation environment.

well as the scaling of this time with the number of robots highlights the online viability of the proposed methodology.

A. Experiment Design and Implementation Details

Shape transition and splitting and merging scenarios are presented for teams of $N = \{4,\,6,\,8,\,10\}$ robots, where each scenario is evaluated through ten simulation trials. In the case of shape transitions, each trial consists of robots instructed to transition between a pair of arbitrary shapes selected at random from a set of known geometries such as those depicted in Fig. 3. In the case of shape transitions, the goal pose of the desired shape is also selected at random (within a bounded workspace). In the case of splitting and merging, each trial consists of an arbitrary split of $k \geq 2$ smaller formations that are selected at random (as above) with a similar random rotation and translation applied to the desired shape trajectory. After completing the split maneuver, the robots are instructed to merge into a single larger formation. A high fidelity simulation environment is implemented in MATLAB that models the vehicle up to the rotor dynamics and evaluate the algorithm based on the quadrotor model [12].

B. Simulation Results

Figure 7 provides an overview of the performance outcomes associated with the shape transition simulation trials based on the previously discussed criteria and metrics. We observe that feasibility (Fig. 7a) and safety (Fig. 7b) are preserved throughout the simulations based on the corresponding maximum acceleration and minimum clearance distance. We also observe that the corresponding total computation time associated with the algorithm components approaches
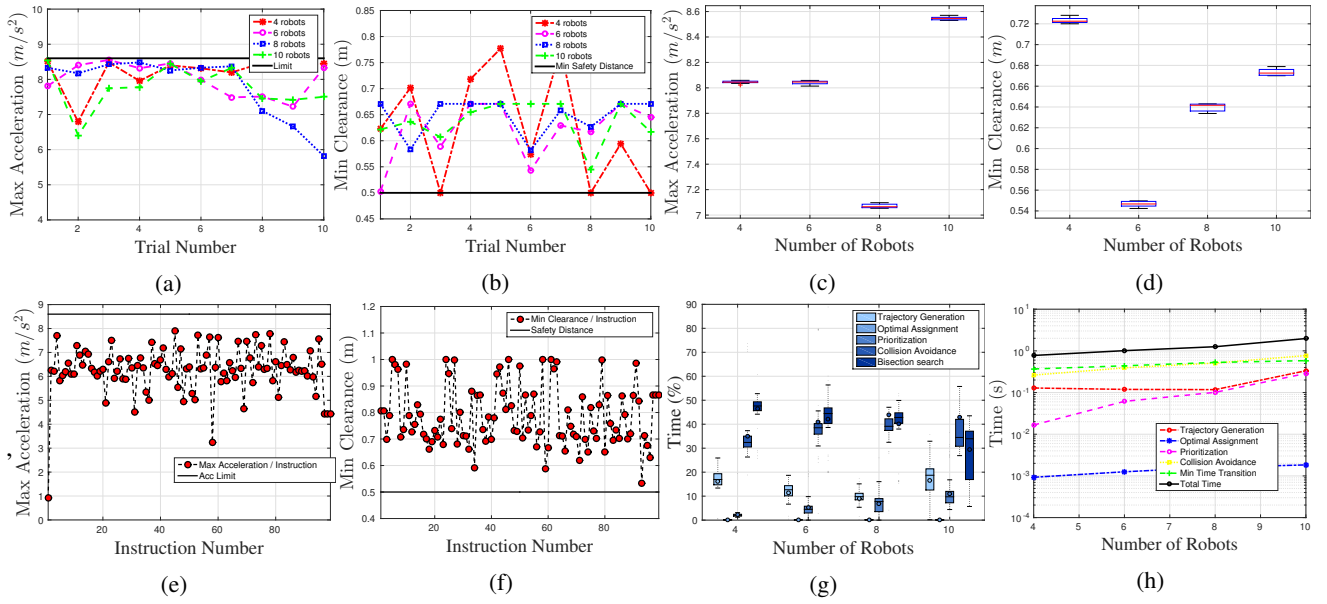
Fig. 7: Shape transition performance for simulation scenarios with varying numbers of robots. Figures 7a and 7b show the maximum acceleration and minimum inter-robot values, respectively, for each simulation trial (10 simulation trials for each value of N). Figures 7c and 7d show the distribution of the maximum acceleration and minimum clearance values for a single simulation trial repeated 10 times; highlighting the repeatability of the simulation. Figures 7e and 7f show the maximum acceleration and minimum clearance values per shape transition for an extended simulation carried out with 4 robots and 100 arbitrarily selected shapes. The time characterization of various stages of the planning strategy during shape transitions is presented in Figs. 7g and 7h.
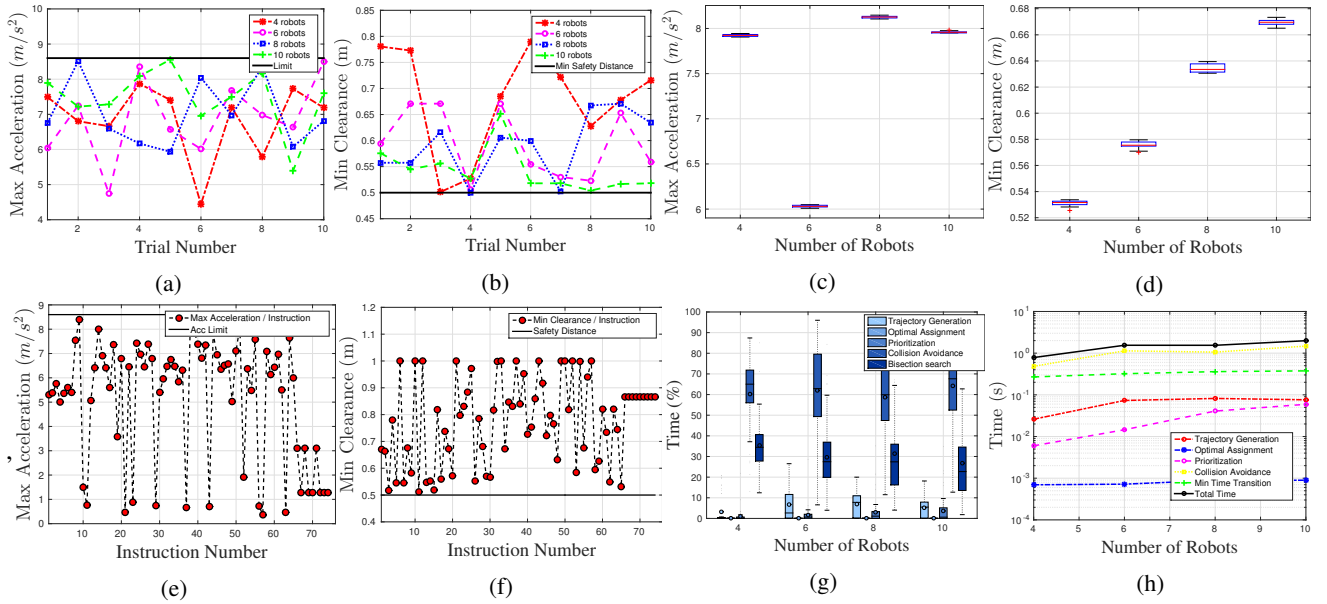

Fig. 8: Group split and merge performance for simulation scenarios with varying numbers of robots. Figures 8a and 8b show the maximum acceleration and minimum inter-robot values, respectively, for each simulation trial (10 simulation trials for each value of N). Figures 8c and 8d show the distribution of the maximum acceleration and minimum clearance values for a single simulation trial repeated 10 times. Figures 8e and 8f show the maximum acceleration and minimum clearance values per split and merge behavior for an extended simulation carried out with 10 robots and 100 arbitrarily selected shapes. The time characterization of various stages of the planning strategy during splitting and merging experiments is presented in Figs. 8g and 8h.

1 s for teams of 10 robots (Fig. 7h) given an unoptimized   MATLAB code based. While 1 s is an acceptably low time

in the context of our application as complex gestures can take the performer several seconds to generate, we anticipate an optimized implementation would dramatically reduce this computation time.

The repeatability of shape transitions is evaluated through the distribution of maximum acceleration (Fig. 7c) and minimum clearance (Fig. 7d) for a subset of simulation trials. From Fig. 7, it is clear that the variation in system performance over multiple trials is negligible despite the arbitrary or random selection of desired shapes and pose configurations.

Similar observations and conclusions may be drawn for the group splitting and merging trials (Fig. 8). We note that in all cases the trajectories remain safe, feasible, real-time viable, and consistent across a large number of simulation trials with varying numbers of robots.

We also consider the ability of the system to generalize to a large number of shape transitions and split or merge scenarios that arise during operation. The generalizability of the planning approach for shape transitions is evaluated through an extended simulation where four robots transition between 100 randomly selected pairs of shapes (Fig. 7e and Fig. 7f). In the case of splitting and merging, a team of ten robots are instructed to split into shapes selected at random and then merge back into a new random shape. In either case, we observe that safety and feasibility are preserved per the metrics detailed above (Fig. 7e and Fig. 8f).

IV. CONCLUSION AND FUTURE WORK

The paper presents an online strategy for coordination and control of large teams of quadrotors for the purpose of visual narration in an unscripted theatrical performance. In order to preserve the aesthetic appeal as well as the visual connection between the operator input and the team response, we propose a formulation that enables real time operation and generates plans that are near time optimal (visually appealing), feasible, and safe. The planning approach is evaluated via extensive simulation trials and is shown to generate dynamically feasible and non colliding robot trajectories in real time during shape transitions and splitting and merging of formations. While our approach has been tested extensively in simulation, in the future we plan to validate its efficacy in a real robotic environment with large teams of physical quadrotors.

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