Multi-Party Flight Trajectory Negotiation for Upper Class E Traffic Management

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Abstract*—A new operational concept has been proposed in Upper Class E airspace at or above 60,000 feet (Flight Level / FL600), which will allow operators of diverse vehicle characteristics to cooperatively manage and share their operational intents with neighboring operators to avoid conflict. There is a consensus in the community that negotiation for strategic deconfliction is needed, but there are no specific guidelines for how the negotiation should be conducted. There is a need for a structured and cooperative way to resolve the conflict between a wide variety of aircraft projected to be operating in Upper Class E for the negotiation to be carried out routinely. The use of negotiation models are a promising solution that can resolve conflict risks during flight in real-time while taking into account the uncertainty of future vehicle positions and dynamic business considerations. A two-party negotiation model has been researched, but as the traffic demand grows, there is a higher likelihood of conflict involving multiple aircraft that would require a method to handle multi-party conflict. This paper proposes a cooperative multi-party negotiation model inspired by game theory concepts for application to flight trajectory negotiation in Upper Class E traffic management. This model can be applied in flight with operators communicating directly after a potential conflict is detected. Some of the model's benefits include allowing business costs to be private to operators, allowing operators to collaborate together to find conflict-free flight trajectories, and being compatible with different aircraft and operation types. This model provides a structured procedure for conflict resolution that can handle conflict involving multiple parties, assuming each operator is willing to take on a small cost to themselves in order to reduce the total cost to the group.

***Index Terms*—Negotiation Model, Air Traffic Management**

I. Introduction

The aviation technology is expanding both figuratively and literally into heights above 60,000 feet (Flight Level / FL600). Currently, this airspace Upper Class E, is mostly used for military operations and has no specific guidelines for civil aircraft operations. Air traffic operations in Upper Class E present unique challenges for a variety of reasons. There are limited services provided by the current National Airspace System (NAS) and there are a vast diversity of aircraft that are expected to operate in the near future in Upper Class E airspace. Supersonic transport, High Altitude Long Endurance (HALE) fixed-wing vehicles, HALE balloons, high-speed unmanned fixed-wing aircraft, HALE airships, and other vehicles designed for space launches will either operate or pass through Upper Class E airspace [1]. These vehicles have different levels of maneuverability, speed, weight, size, flight duration, and control, making it difficult to find ways for these vehicles to safely and fairly operate together in shared airspace. Operations in Upper Class E airspace can often have long missions and are usually associated with uncertainty about predicted future vehicle positions. All of these unique features lead to the challenge that it is nearly impossible to adhere to strict flight trajectories while in this airspace, and therefore planning conflict-free flights before entering or exclusively reserving airspace for specific operations is not feasible. Vehicles in Upper Class E airspace must deconflict their intended flight trajectories strategically during flight.

To handle the challenges described above, a new Upper Class E Traffic Management (ETM) concept has been proposed to cooperatively manage the airspace, with operators managing and sharing their flight intents. In accordance with the version 1.0 ETM Concept of Operations provided by the FAA [2], NASA, the FAA, and industry stakeholders have been collaborating to develop a system for ETM, in which the vehicle operators have the flexibility to negotiate how they deconflict with vehicles that are projected to be in conflict without the involvement of air traffic service providers. Cooperative traffic and conflict management is a core tenet of ETM concept. Although there has been a general consensus to engage in good-faith negotiations for managing strategic conflicts, no guidelines have yet been established. Ad-hoc negotiation has been suggested as an initial step, but a structured approach that can provide guidelines for operators to follow could ensure fairness and consistency.

A bilateral negotiation model [3] was developed specifically for use in conflict resolution between aircraft in ETM. This model is based on game theory and provides the structure for operators to negotiate while ensuring a solution is found. Although the two-party negotiation model proposed earlier shows promise, it needs to be expanded to handle conflicts involving multiple parties if it were to provide a complete and more comprehensive solution in a high-traffic-density environment. The model for a flight trajectory negotiation proposed in this paper is based on the two-party negotiation

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model but has been extended to handle conflict involving multiple parties. For negotiation to be possible, a collaborative air traffic management system will need to exist and operate under the assumption that all operators within the airspace are willing to cooperate and share operational intents. The two-party model in [3] and this multi-party extension provide the structure and rules for operators to follow during negotiation to produce new conflict-free flight trajectory plans for all operators.

One of the key features of this multi-party negotiation is that while operational intents need to be shared, the details of the operators' mission, such as operation cost, can be kept private. By using principles from game theory, this model can guarantee that if an equitable solution exists, it will be found given a reasonable time frame. Once an agreement is reached, there is clear transparency to all the operators of the new flight trajectory plans of their own and other operator(s) have committed to. The solution set of the conflict-free flight trajectory plans found through negotiation is mutually agreed upon and equitable since all operators share the responsibility and absorb partial costs. No single operator needs to take full responsibility and cost.

The remainder of this paper is organized as follows. In Section II, related work is introduced, providing a background for both conflict resolution in ETM and multi-party game theoretic models, as well as highlighting the need for a multi-party negotiation. Then, Section III outlines the key concepts and details for this negotiation model. Section IV presents an example that validates the model's effectiveness in real-world air traffic scenarios involving three operators. Finally, a summary is provided at the end in Section V with remarks for the direction of future work.

II. Background and Literature Review

Currently, many conflict resolution methods are available for air traffic management, but those methods are neither suitable for ETM nor handle situations with more than two operators. A simple multi-party conflict scenario with three vehicles could have all three vehicles coming into conflict simultaneously. Another way to consider multi-party conflict is with three vehicles having only pairwise conflict at different instances, but solving the conflict with pairwise methods between only two of the three operators could potentially affect or worsen the conflict involving the third operator. To develop a conflict resolution method that is suitable for ETM and multi-party, we extend the research from [3] and incorporate ideas from multi-party game theory models. This section will cover some of the current conflict resolution methods for traffic management and some relevant multi-party game theory models.

A. Current Conflict Resolution Methods for Traffic Management

Many cooperative conflict resolution methods have been explored in previous studies [3]–[9] for their use in air traffic management. Many of these studies [3], [5]–[7] can only handle conflict scenarios with two operators, and those that can handle multiple operators [4], [8], [9] are insufficient to meet the needs of ETM. A paper by Park [4] proposes a multi-party negotiation model but only covers aircraft merging from two paths to one. [9] also proposes a multi-party model but treats the conflict as multiple two-party cases. [8] proposes a multi-party negotiation model that relies on a centralized, third-party arbiter to make decisions. In such studies as [4], [7], [8], negotiation is done through mediation where operators do not negotiate directly with each other. Communication done through a mediator could potentially create a communication delay. Several other studies [4]–[6] require that, at each step, operators generate 6 alternative flight trajectory plans corresponding to heading changes (turn left/turn right), altitude changes (climb/descend), and speed changes (acceleration/deceleration). This can be computationally expensive when compared to the two-party cooperative negotiation model in [3], where operators do not need to generate more than one trajectory at each step, and operators are not required to respond to specific dimensions as long as their flight trajectory plan increases the distance from the original flight trajectory plan.

The recent study in [3] introduces the details of the aforementioned negotiation model that does not require operators to propose flight trajectory plans in multiple dimensions, hides private business costs, and guarantees a solution to be reached in a given time frame. This two-party negotiation model guarantees a solution and forces operators to make fair offers and accept fair responses. This model is ideal for ETM but is only for two parties and does not have a defined way to solve conflict if multiple operators are involved, which highlights the need for a multi-party model specific to ETM. The multi-party situation can include scenarios in which all the operators have a potential conflict or only two operators conflict with each other, while the negotiated solutions for their conflict might cause a potential conflict with another operator nearby. By extending the two-party model to multiple parties, we can create the framework for three or more operators to find conflict-free flight trajectory solutions in a variety of situations.

B. Related Work in Game Theory

Game theory models determine how actions and strategies affect outcomes of situations by applying principles of game theory to conflict resolution, where we can ensure certain outcomes based on several assumptions and given that a solution exists. The ideas in game theory methods can be used to define rules and structure in negotiation involving multiple operators. Currently, there is no theoretical multi-party negotiation model that can be directly applied to conflict resolution for air traffic management in ETM. Instead, ideas and concepts from multiple models are combined to develop a negotiation model capable of handling conflict scenarios with more than three operators in this research.

Multi-party conflict resolution in ETM can also be classified as a multi-issue problem, in which there is more than one single problem to solve and negotiate over. Each pair of operators will have a minimum distance between each other to maintain, which can be regarded as separate issues that need to be negotiated over. Previous work has not been able to cover multi-party, multi-issue negotiation in which the solution to each issue will interact with the solution of all other issues. Some bilateral multi-issue models [10]–[12] can give insight into how to handle multiple issues simultaneously. One option could be simplifying an issue into solving multiple bilateral negotiations in [10]. Bac and Raff [11] developed a bilateral model that allows players to make an offer on either one issue at a time or all issues in a package. Once an issue is resolved, it is removed from the set of negotiable issues. Fershtman [12] proposes handling separate issues one at a time by first deciding a pre-determined order to solve each issue. This is not ideal for air traffic management because these solutions do not consider the interactions between each issue. If one bilateral conflict is solved without consideration of other nearby conflicts, then the solution to the first conflict could increase the risk of the second or potentially cause a new conflict.

Many multi-party models [10], [13]–[16] in game theory require players to make offers on behalf of other players. But for this research, an operator or player can only make offers of their own flight trajectory and cannot suggest a flight trajectory for another operator to fly with. A multi-party negotiation and planning model used in a robot movement [15] does not require players to make offers on behalf of others, which may provide a framework that could be used in our problem. In their model, agents take turns making partial offers specifying only how they will move. Once an offer is revealed, all other agents calculate their utilities based on how they must move in response. Players will not know the cost or utility of their plan relative to other players until after it has been revealed and other players have calculated their responses. In the exit game model [14], a player who agrees to a proposal has their utility fixed at that offer for all subsequent rounds. The player can then disregard the following rounds since they have a fixed utility. This is also referred to as the player 'exiting' negotiation, which is also used in [15]. This idea could be used to negotiate conflict-free flight trajectories by allowing negotiation to occur in rounds, and operators can have their flight trajectories and utilities fixed for one round. Once an operator submits a response, they will not be affected by subsequent responses in the same round. However, operators will not be able to exit all rounds of negotiation early since a fixed flight trajectory might introduce a constraint to other operators that will force them to take a higher cost or block a potential solution. Operators will need to stay in negotiation until a final solution is reached that is agreeable to all players.

III. Multi-Party Negotiation Model

Before introducing the negotiation model, this section first relates the negotiation to concepts introduced from game theory. The key concepts to game theory, such as cost and utility, as well as concepts relevant to air traffic management, such as conflict risk assessment, are described, after which the specifics for the cost and utility functions of the negotiation model are introduced. Then, we will define the model assumptions, followed by details of the specific actions that can be taken during negotiation. Finally, the formal model for the negotiation process is described. Table I defines the notations used in the following sections.

TABLE I: Definitions and notations used

$n \in \mathcal{Z}$	The number of operators in negotiation.
$k \in \mathcal{Z}$	The number of operators active in the current round, where $0 \leq k \leq n$.
$rc \in \mathcal{R}$	The required cost, constrained by $0 \leq rc \leq 1$.
x_i	The ith operator, where $i = 1, 2, \ldots, n$.
f_i	A new trajectory associated with the ith operator.
$f_{i,0}$	The original trajectory for operator x_i.
$f_{i,B}$	The baseline trajectory for operator x_i.
$\mathcal{F}_p$	The set of size k, containing trajectories in the current proposal.
$\mathcal{F}_0$	The set of size n, containing all the original trajectories for each operator.
$\mathcal{O}$	The set of size n, containing all operators in negotiation, $\mathcal{O} = \{x_1, x_2, \ldots, x_n\}$.
$\mathcal{A}$	The set of size k, containing operators still active in the current round.
$\mathcal{D}$	The set of size $n - k$, containing inactive operators in the current round.
$\mathcal{CR}_i$	The set of the response costs for operator x_i.
$\mathcal{CP}_i$	The set of the proposal costs for operator x_i.
δ_i	The normalized flight distance of operators x_i.

A. Game-theory Motivated Modeling Approach

In our research, we assume that negotiation occurs simultaneously in rounds in which an operator proposes a new flight trajectory, and all other operators sequentially calculate their response flight trajectory and its associated cost and utility. The cost and utility are concepts in game theory that measure how much a player loses or gains from any given offer [15]. Agents take turns revealing offers, and once an offer is revealed, all other agents calculate their utility. Once an operator submits a response flight trajectory, they temporarily 'exit' negotiation, and their cost and utility are fixed at that flight trajectory until the current round ends. This is similar to the exit game model in [14] and is also used in [15] where once a player agrees to a proposal, their utility is fixed, and the player 'exits' negotiation. By fixing utility or cost in each round, operators can respond asynchronously. This may make responding earlier advantageous to operators.

B. Key Concepts

The concepts covered in this section include cost and utility, conflict risk assessment, and different kinds of flight trajectories used in negotiation.

1) Cost and Utility in Game Theory: Cost and utility in game theory quantify how much a player gains and loses in each offer. By defining a cost and utility function, we can make conclusions about whether a solution can be reached or not. In our model, we impose a constraint on the cost function, to be defined later, that specifies the minimum amount of cost a player must incur in their current offer. This constraint increases with time, forcing operators to make higher concessions for each round. This follows the multilateral monotonic concession protocol from [17] in which, in the first round of negotiation, players are free to make an initial proposal at any cost, and in each of the following rounds they must either remain at their current proposal or make a new proposal at a higher cost. This process repeats until no agent is willing to make a new proposal or an agreement is reached.

2) Conflict Risk Assessment: Before operators can enter a negotiation, conflict risk needs to be assessed during flight. Conflict between two vehicles can be defined with an associated probability of conflict surpassing a predefined threshold. A probabilistic operational intent model from [18] can be used to detect potential conflict probability by checking for conflict within overlap in predicted operational intents. If desired, risk can be incorporated into our model to determine a combined measurement for both the likelihood of an undesired event and the harm-based risk associated with the undesired events [19]. Then, negotiation can be triggered by the risk threshold being surpassed. This probability would determine the risk of the two vehicles coming into contact sometime in the future. When more than two operators are involved, each aircraft pair will have separate conflict probabilities.

3) Original and Baseline Flight Trajectory Plans: The original flight trajectory of an operator x_i, $f_{i,0}$, is the plan that the operator is currently flying at the start of a negotiation. The baseline flight trajectory of an operator x_i, $f_{i,B}$, is the plan that the operator must fly to avoid conflict with all other operators fully, assuming no other aircraft can change from their original flight trajectory plans. This paper uses these two types of flight trajectories for comparison since the ideal situation for any operator would be to continue with their original flight trajectory. The least favorable option for any operator would be to have to fly their baseline flight trajectory. Our model is applied to find a reasonable path for each operator somewhere in between their baseline and original flight trajectory.

C. Specifications of Cost and Utility Functions

Every operator in the negotiation has a set of costs associated with their own flight trajectory. A single operator has one cost and one normalized flight distance; normalized flight distance is defined in the following section in negotiation.

1) Normalized Flight Distance: This model allows operators to keep their true business costs private by building a relationship between the amount an operator maneuvers from their original flight trajectory and cost. The flight distance is normalized to a percentage where a 0% normalized flight distance represents the original flight trajectory of the operator, and 100% is used for the baseline flight trajectory. The normalized flight distance of an operator x_j can be written as δ_i where the input f_i represents a new flight trajectory of operator x_i. $D(f_i)$ is defined as the new distance of the operator x_i. To find the normalized flight distance of any flight trajectory f_i for operator x_i, we find the flight path distance of the original plan ($f_{i,0}$), the new plan (f_i), and the baseline plan ($f_{i,B}$) [20]. The normalized flight distance is the ratio of the additional flight distance in this proposal over the extra flight distance that would have been incurred in the baseline flight trajectory, as shown in the equation below.

$$\delta_i(f_i, f_{i,0}) = \frac{D(f_i) - D(f_{i,0})}{D(f_{i,B}) - D(f_{i,0})} \tag{1}$$

2) Cost and Utility: Under the assumption that the baseline flight trajectory will have the highest cost and that the original flight trajectory will have the lowest cost, we can represent the true cost to be a percentage in which 100% cost is the cost to fly the baseline flight trajectory and 0% cost is the cost to fly the original flight trajectory. This cost percentage can be denoted by c_i, where the cost is defined for operator x_i to solve conflict with operator x_j. We assume that the original flight trajectory has the lowest cost because we want to measure the additional cost to the operator solving conflict; therefore, by staying on their original flight trajectory, the additional cost is 0%. We also define utility as $1 - c_i$. Each time an operator takes on more cost, their flight distance becomes larger, and the process will move closer to reaching a final agreement. The relationship between cost and normalized flight distance represents how the operators value the cost of maneuvering from their original flight trajectory. Some operators may have a higher true cost at the same normalized flight distance as others. To account for this, we introduce the β variable to measure how much each operator values the normalized flight distance cost. The equation is shown in (2) which describes the relationship between cost and normalized flight distance. For different values of β, the relationship can translate to operators valuing each percentage of normalized flight distance at a higher or lower cost percentage. Fig. 1 shows how the value of β affects the relationship between cost and normalized flight distance.

$$c_i = \delta_i^{\frac{1}{\beta}} \tag{2}$$

3) Required cost: To ensure a solution is found, the minimum cost an operator must incur in each proposal is

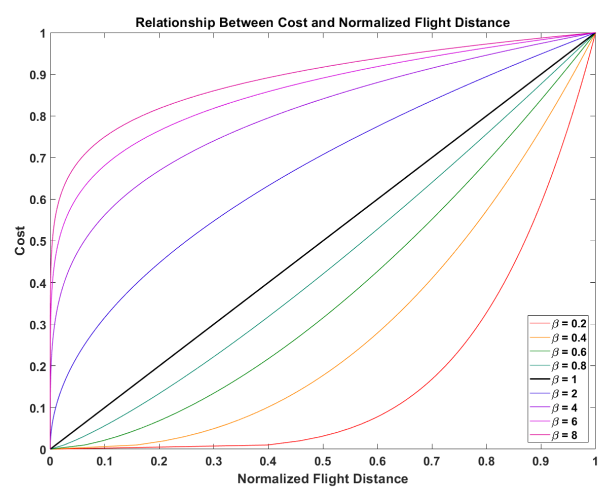

Fig. 1: The relationship between normalized flight distance and cost for different values of β.

constrained by the required cost variable rc. This variable is common among all operators and is based on the current time and the time given to negotiate. It also forces an operator to accept an offer if their response cost is lower than the rc [3]. To find rc, first define the negotiation window with a given start time t_{start} and end time t_{end}. This start time should be when all operators enter a negotiation, and the negotiation time window must end before the first aircraft loses the ability to avoid conflict. The duration of negotiation is then equal to $t_{end} - t_{start}$. For any interval t_{cur} between the start and ending time such that $t_{start} \leq t_{cur} \leq t_{end}$. The rc is defined as a function of the current time shown in (3). The rc is constrained by $0 \leq rc \leq 1$, where the value of rc will be 0 when t_{cur} = t_{start} and 1 when t_{cur} = t_{end}.

$$rc(t_{cur}) = \frac{t_{cur} - t_{start}}{t_{end} - t_{start}} \tag{3}$$

D. Model Assumptions

Our negotiation model relies on several assumptions. The following assumptions are needed to predict the behavior of operators and ensure a solution is found. The negotiation model can only operate properly when these assumptions can be reasonably made.

- Operators are rational and have the goal of minimizing their own costs and maximizing their utilities.
- Operators will always consider the lowest cost response flight trajectory plan.
- Current and proposed flight trajectories are shared among all operators in negotiation.
- Operators are not aware of the strategies of other operators in the negotiation because the true cost is not shared.
- Operators are willing to cooperate and follow the required cost constraint.
- The original flight trajectory has the lowest cost and is the most ideal plan for every operator in negotiation.
- The baseline flight trajectory has the highest cost and is the least ideal plan for every operator in negotiation.
- When an operator submits a proposal trajectory, it will not create new conflict with other operators.
- No new operators enter the air space and join the negotiation when the negotiation already started.

E. Negotiation Actions

The negotiation process comprises a series of rounds that build a final set of conflict-free flight trajectories. The set of all operators in negotiation can be represented by $\mathcal{O}$, which has size n. In each round, an operator can only propose or respond once. After an operator submits their response or proposal trajectory, they become inactive for the remainder of the round. The active and inactive operators in the current round are denoted by $\mathcal{A}$ and $\mathcal{D}$, respectively. The relationship between $\mathcal{O}$, $\mathcal{A}$, and $\mathcal{D}$ can be defined mathematically as $\mathcal{O} = \mathcal{A} \cup \mathcal{D}$. Each round is started by an operator proposing a valid flight trajectory. The set of flight trajectories that have been submitted by all operators at the time in set $\mathcal{D}$ in the current round can be denoted by $\mathcal{F}_p$. Once a proposal is submitted, the proposing operator is removed from set $\mathcal{A}$ and joins set $\mathcal{D}$, i.e., a group of operators who have submitted flight trajectory plans and are silent observers until the round ends. Each time an operator submits a response flight trajectory, they become a silent observer joining set $\mathcal{D}$, leaving set $\mathcal{A}$, and their submitted flight trajectory is included in set $\mathcal{F}_p$. All other operators who have not submitted a flight trajectory or made the initial proposal are considered active in the negotiation round and are included in set $\mathcal{A}$.

A round can end either by any operator rejecting the proposal or by an agreement being reached. If an operator rejects a proposal, the round will end, and a new one can begin. A round ending means all operators are active again, i.e., $\mathcal{A} \leftarrow \mathcal{O}$, $\mathcal{D} \leftarrow \{\}$, and the set of submitted flight trajectories become empty $\mathcal{F}_p \leftarrow \{\}$. An agreement is reached once the last active operator submits a flight trajectory while all other operators have successfully submitted valid flight trajectories without rejecting the proposal. At this point, the set of active operators will be empty, and the sets of inactive operators and the set of flight trajectories will be of size n. The remainder of this section will cover the details of the proposal and response flight trajectories.

1) Proposing: A new negotiation round begins with a proposed flight trajectory. Any operator can propose the first flight trajectory if it meets the required cost constraint, ensuring that the cost for the flight trajectory for the proposing operator is higher than the required cost [3]. When an operator proposes, it generates some proposal trajectories and the trajectory with the lowest associated cost will be selected. The chosen trajectory is then submitted into the set $\mathcal{F}_p$, forming the joint offer that could potentially be the final solution for the negotiation round. With the submission of only one proposal $\mathcal{F}_p = \{f_i\}$, the operator x_i is now considered inactive for the remainder of the current round. This step marks a critical point in the negotiation process as it sets the stage for subsequent responses and adjustments by other active operators.

2) Responding: Once a round has started, only active operators that conflict with inactive operators can submit a response flight trajectory. The operator must calculate a flight trajectory that resolves conflict with all the valid submitted flight trajectories from the inactive operators. The response flight trajectory also meets the required cost constraint, meaning the response cost is lower than the required cost. Operators can generate multiple response trajectories with associated costs, and the trajectory with the lowest cost will be selected. During the response phase, the operator primarily focuses on resolving conflicts. If the response cost is less than or equal to the required cost, it must accept submitted flight trajectories. There may be instances where the response cost is higher than the required cost. Under these circumstances, operators can reject the current offer, as they could potentially propose a new plan with a cost lower than that from their current response flight trajectory. If the operator chooses or is required to submit their flight trajectory, then the operator is considered inactive in the current round, and the flight trajectory joins the set $\mathcal{D}$.

3) Simultaneous Process: In the negotiation model, instead of randomly picking an operator and waiting for that operator to finish its turn, a simultaneous mechanism can allow all operators to generate new proposals or response plans concurrently, enhancing both the efficiency and realism of the process. Basically, all operators are allowed to generate new trajectories at the same time. Once there is an operator finishes generating its plan, this operator will submit or reject its new plans based on the cost constraint, and the remaining operators will stop generating their new plans. All active operators without existing conflicts with inactive operators can generate proposal trajectories. Meanwhile, all those identifying conflicts with inactive operators generate response trajectories to resolve these conflicts. The operator x_i that finishes generating its new plan first submits it to $\mathcal{F}_p$, and then the operator x_i is considered inactive for the current round. This approach significantly reduces negotiation time and efficiently supports scalability by managing multiple operators. A simple method is developed to determine whether the operator needs to generate a proposal trajectory or a response trajectory. Algorithm 1 in the Appendix provides the detailed logic of this method.

F. Modeling of Negotiation Process

Once all parties have agreed to negotiate, a negotiation window must be defined to calculate the required cost, and the negotiation loop can begin at step 0. With the negotiation actions and other details outlined above, the negotiation process is shown in Fig. 2 and can be simplified as the following list of steps.

Step 1: All active operators calculate a proposal flight trajectory f_i and their proposal costs $\mathcal{CP}_i$.

Step 2: Check if $cp \in \mathcal{CP}_i$, $cp \geq rc$. If true, continue to step 3; otherwise, repeat steps 1-2 until a valid flight trajectory is found.

Step 3: Operator x_i who submits their lowest cost proposal plan first becomes inactive in the current round. Other operators are signaled to stop their current actions.

Step 4: For every active operator x_j that conflicts with x_i, x_j generates response plans. For every active operator x_k that does not have a conflict with x_i, x_k generates proposal plans.

Step 5: There are two cases:

- If x_k finishes generating its plans first, whose costs are greater than the required cost, continue to step 3. Other operators stop their current actions.
- If x_j finishes generating its plans, f_j resolves conflicts with all submitted flight trajectories first, then continues to step 6. Other operators stop their current actions

Step 6: If the response cost from f_j is less than or equal to the required cost, proceed to step 9; otherwise, go to step 7.

Step 7: Operator x_j can choose to accept or reject the current proposal. If chosen to reject, go to step 8; otherwise, if it is accepted, proceed to step 9.

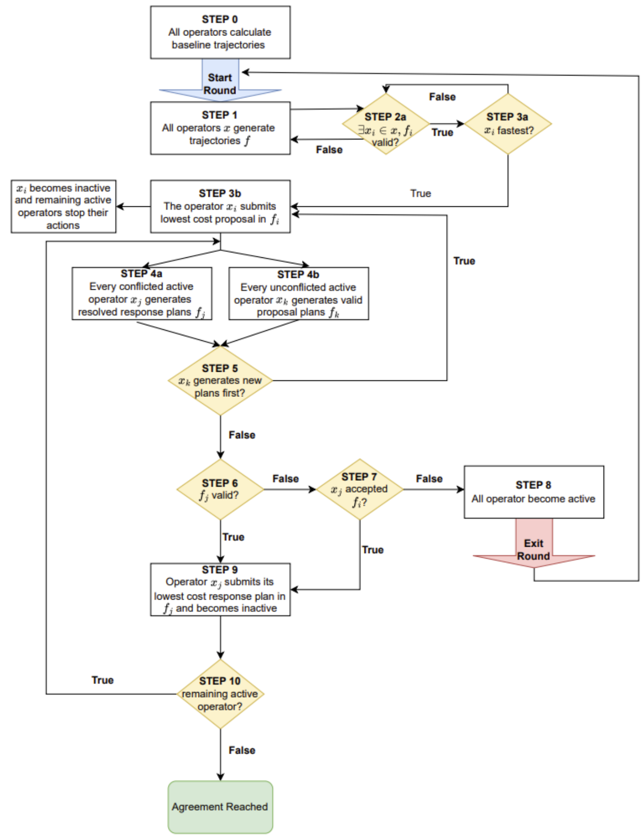

Fig. 2: The general process of negotiation. The main loop shows a single round of negotiation. If the loop ends up in Exit Round, then a new round can begin.

Step 8: Operator x_j rejects the current proposal, all operators become active again, and a new round begins, starting over from step 1.

Step 9: Operator x_j submits f_j and becomes inactive in the current round.

Step 10: Check if all operators have submitted a flight trajectory or, equivalently, that all operators are inactive. If all operators are inactive, an agreement has been reached, flight trajectories can be finalized, and the negotiation ends; otherwise, repeat step 4 until all operators have submitted a flight trajectory.

Algorithm 2 in the Appendix describes an active and fastest operator's approach to generate its new trajectory.

IV. Illustrative Example of Multi-party Negotiation

In this section, we conduct an example to illustrate the negotiation process model in Upper Class E airspace when three operators are involved.

A. Example Setup

We simulate a scenario within Upper Class E airspace involving three distinct aircraft: operators A, B, and C. These operators are projected to enter a shared airspace from different vectors. Operator A's flight path is designed to intersect with operator B's and operator C's paths at different flight trajectories. Therefore, we had two conflict sets (A, B) and (A, C). An example of how a conflict set can be modeled in a real-world scenario can be seen in Fig. 3, which shows the original trajectories of three operators. In this case, all three operators are operating a Global Hawk fixed-wing aircraft at a constant speed of 340 knots with a mean value wind sum of 0 knots. The conflict pairs (A, C) and (A, B) have a negotiation t_{end} time budget of 52 minutes and 66.7 minutes. Their relative likelihood of conflict are 99% and 100%, which indicates an urgent need to resolve conflict, based on the conflict assessment and risk reduction model from previous work [20].

B. Walkthrough of the Negotiation Process

The following example provides a comprehensive walkthrough of the multi-party negotiation process as applied in an ETM scenario. This detailed scenario illustrates the dynamic interaction among three operators: A, B, and C, as they navigate through successive rounds of proposing and responding to flight trajectories with a left heading change (left plan) and a right heading change (right plan) within a predefined negotiation framework. The example emphasizes the practical application of the theoretical concepts detailed in the "Negotiation Actions" and "Modeling Negotiation Process" sections. Each step is designed to reflect the negotiation dynamics, highlighting how operators transition between active and inactive states and make strategic decisions based on cost. This walkthrough aims to bridge the gap between the theoretical models and the real-world applications, providing a clear view of the negotiation process in action and demonstrating the complexity and strategic depth of multi-party negotiations in ETM systems.

In this context, an iteration concludes once an operator submits its new plan. A round finishes when all operators are inactive. Therefore, a round can have a maximum of three

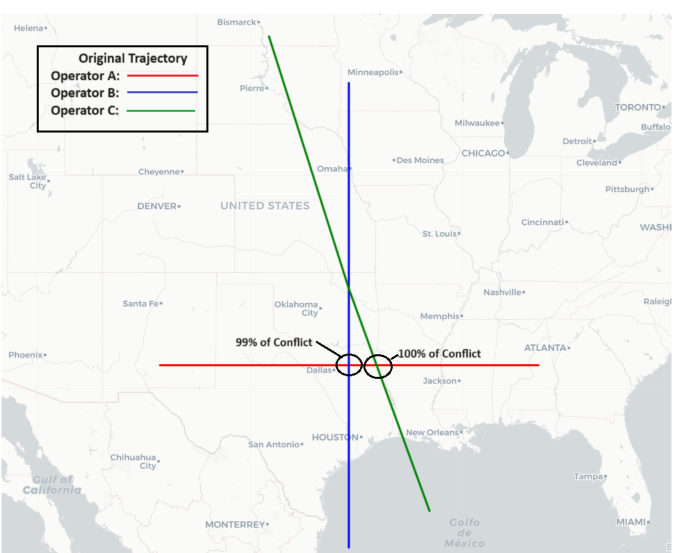

Fig. 3: The original trajectory of operator A, B and C.

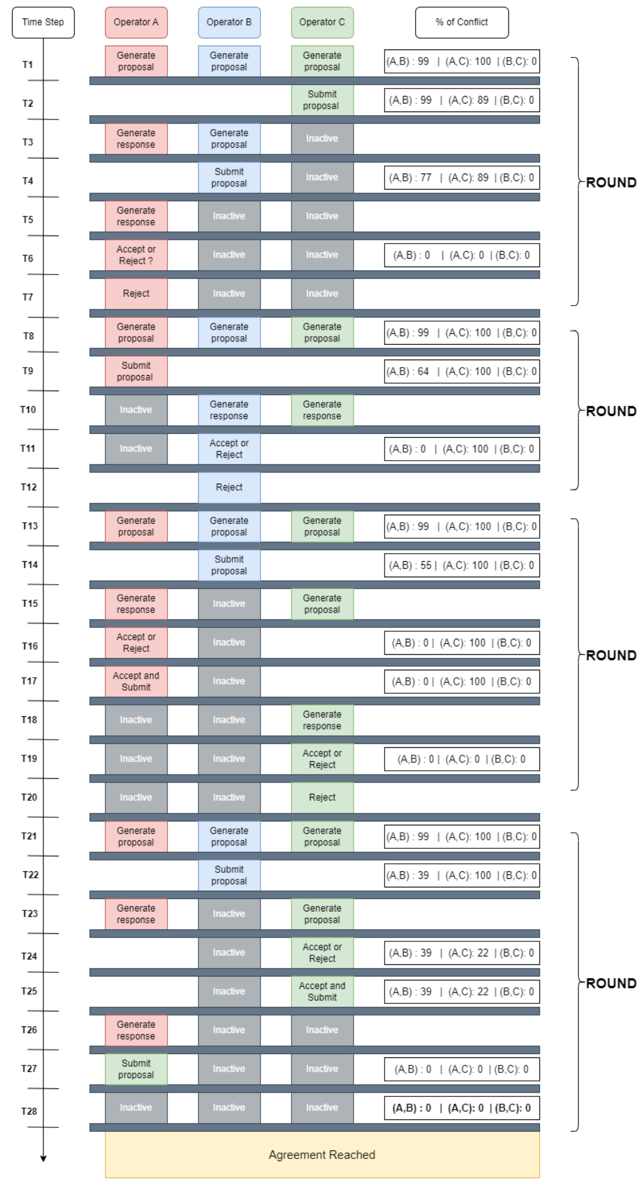

Fig. 4: The process of negotiation.

iterations since we have three operators. Fig. 4 shows the time steps, each operator's action state, percent of conflict likelihood in each iteration, an the number of negotiation rounds. Table II presents the cost of each operator in each round. The Table shows the required cost for each round and the cost of each operator's proposed or response plans for two alternative paths (i.e. path taking left or right turn to avoid the conflict). The bold highlight indicates the cost that was chosen and submitted by the operator.

TABLE II: Costs in each round.

Round	Required Cost	Operator	Left Turn	Right Turn
1	0.0263	C	0.0860	**0.036**
1	0.0371	B	0.3824	**0.0440**
1	0.0837	A	1.1712	**0.5621**
2	0.0871	A	0.2742	**0.0883**
2	0.0993	B	1.4483	**0.2213**
3	0.1260	B	0.3824	**0.1329**
3	0.1360	A	0.7972	**0.0719**
3	0.1925	C	1.5740	**0.7145**
4	0.1935	B	0.3824	**0.1943**
4	0.2689	C	0.2719	**0.2699**
4	0.3069	A	1.3918	**0.2131**

Detailed step-by-step descriptions of the negotiation process, as shown in Fig. 4, are as follows:

Round 1: First Iteration (from T1 to T2 in Fig. 4):

- All operators simultaneously generate their proposal trajectories.
- Operator C completes first with two plans. The required cost is 0.0263. The left plan has a proposal cost of 0.0860, while the right plan's cost is 0.036, shown in the first row of the Table II.
- Operator C submits the right plan with a cost of 0.036 and becomes inactive.
- Conflict percentage between operators A and B is 89%.

Second Iteration (from T3 to T4 in Fig. 4):

- Operator A starts generating response plans to resolve conflict with operator C.
- Operator B, not directly conflicting with C, continues proposal plan generation.
- Operator B finishes first and submits its right plan costing 0.0440, which is higher than the required cost of 0.0371. Operator B becomes inactive.
- Conflict percentage between operators A and C is now 77%.

Third Iteration (from T5 to T7 in Fig. 4):

- Operator A generates response trajectories to resolve conflicts between operators B and C.
- The costs of its left and right trajectory exceed the required cost, shown in the third row of Table II.
- Operator A thinks the response costs are too high and rejects the current proposal, which makes all operators active again.
- A new round begins.

Round 2: First Iteration (from T8 to T9 in Fig. 4):

- All operators generate proposal trajectories simultaneously.
- Operator A finishes first. Both costs exceed the required cost of 0.0871.
- Operator A submits the right plan costing 0.0883.
- Conflict percentage with operator B is now 64%.

Second Iteration (from T10 to T12 in Fig. 4):

- Operators B and C generate response trajectories simultaneously due to conflict with A.
- Operator B finishes first; both plans exceed the required cost, leading to rejection of the proposals and activation of all operators.
- A new round begins.

Round 3: First Iteration (from T13 to T14 in Fig. 4):

- All operators generate proposal trajectories simultaneously.
- All plans have costs exceeding the required cost, shown in the sixth row of Table II.
- Operator B submits its right plan, with a lower cost, and becomes inactive.

Second Iteration (from T15 to T17 in Fig. 4):

- Operator A generates response plans. Simultaneously, operator C generates its proposal plan generation.
- Operator A finishes generating its plans first. Operator A's right trajectory has a cost of 0.0719, which is lower than the required cost.
- Operator A submits its right plan and becomes inactive.

Third Iteration (from T18 to T20 in Fig. 4):

- Operator C generates its response trajectories.
- Even though operator C's new trajectories resolve the conflict, their costs are higher than the required cost.
- Operator C rejects the submitted plans, making all operators active again.
- A new round begins.

Round 4: First Iteration (from T21 to T22 in Fig. 4):

- All operators generate proposal trajectories simultaneously.
- Operator B finishes generating its proposal plans first.
- The required cost is now 0.1935. Operator B's right plan costs 0.1943, while its left plan costs 0.3824.
- Operator B submits this right plan and becomes inactive.
- The conflict percentage between operators A and B is 39%.

Second Iteration (from T23 to T25 in Fig. 4):

- Operator A starts generating response plans to resolve conflict with operator B.
- Operator C generates its proposal plan.
- Operator C finishes first and submits its right plan costing 0.2699, which is higher than the required cost of 0.2689. Operator C becomes inactive.
- The conflict percentage between operators C and A drops to 22%.

Third Iteration (from T26 to T28 in Fig. 4):

- Operator A generates response trajectories to resolve conflicts between operators B and C.
- Only its right plan, with a cost of 0.2131, is lower than the required cost of 0.3069.
- Operator A submits this plan and becomes inactive.
- Now, all operators are inactive, indicating that an agreement has been reached and the negotiation has ended.

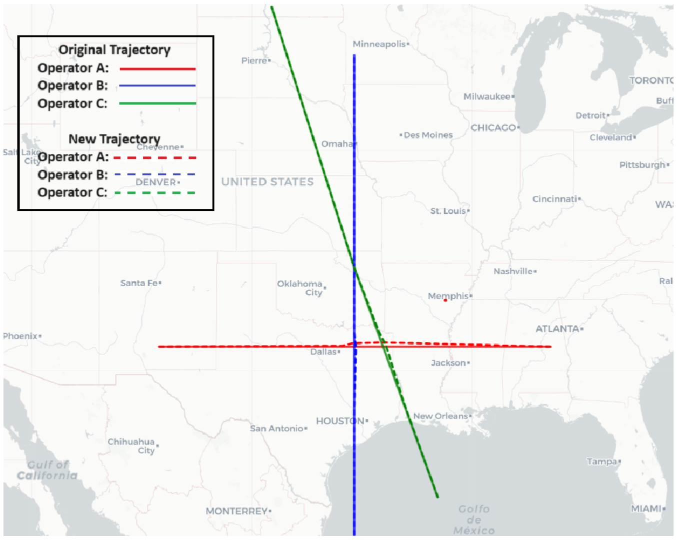

Fig. 5: The new trajectory of operator A, B and C

In this scenario, it takes four rounds for all operators to reach an agreement that all operators are satisfied with their new trajectories. This is an ideal solution since the proposal costs are higher than the required costs, and the response costs are lower than the required costs. However, if the last operator was willing to accept the submitted plans, this negotiation process might have ended earlier, potentially in the third round or even as early as the first round. Therefore, the duration of the negotiation process heavily depends on the operators' willingness and capabilities.

V. Conclusion

This negotiation model offers a structured way to resolve conflict between multiple operators in flight. The time-based required cost and associated constraints for each conflict will force a solution, if one exists, to be found. Since this model provides flight trajectory calculations along with a decision to accept or reject those plans, future work can utilize the automation model developed within [20] to automatically process this model. This also opens up the possibility of performing a sensitivity analysis of the multi-party negotiation model to determine the efficiency of the model. There can also be a mix of manual and automated operators participating in the same negotiation which will allow the level of autonomy in negotiation up to the choices made by the entity carrying out the operation. While this model has been developed to meet the challenges and demands of ETM, the flexibility of this model lends itself to potential uses in other areas of air traffic management. There are potential applications in strategic planning to determine equitable flight path planning.

Although the simultaneous process can help reduce negotiation time, it can also significantly increase the time for a large number of operators. Future multi-party negotiation models could limit the number of times an operator can reject the plans. In addition, more scenarios using the multi-party negotiation model described in this paper need to be tested in the future and compared with the baseline.

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References

[1] H.-S. Yoo, J. Li, J. Homola, and J. Jung, *Cooperative Upper Class E Airspace: Concept of Operations and Simulation Development for Operational Feasibility Assessment*, 2021. [Online]. Available: https://arc.aiaa.org/doi/abs/10.2514/6.2021-2356

[2] "Concept of operations: Upper class e traffic management (etm)," Federal Aviation Administration, Tech. Rep., 2020.

[3] M. Xue, A. K. Ishihara, and P. U. Lee, "Negotiation model for cooperative operations in upper class e airspace," in *2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC)*, 2022, pp. 1–9.

[4] S. G. Park and P. K. Menon, "Game-theoretic trajectory-negotiation mechanism for merging air traffic management," *Journal of Guidance, Control, and Dynamics*, vol. 40, no. 12, pp. 3061–3074, 2017. [Online]. Available: https://doi.org/10.2514/1.G002716

[5] S. Wollkind, J. Valasek, and T. Ioerger, *Automated Conflict Resolution for Air Traffic Management Using Cooperative Multiagent Negotiation*, 2012. [Online]. Available: https://arc.aiaa.org/doi/abs/10.2514/6.2004-4992

[6] A. R. Pritchett and A. Genton, "Negotiated decentralized aircraft conflict resolution," *IEEE Transactions on Intelligent Transportation Systems*, vol. 19, no. 1, pp. 81–91, 2018.

[7] "Atc real ground-breaking operational system (argos)," Maastricht Upper Area Control Centre, Tech. Rep., 2023.

[8] P. Jarvis, S. Wolfe, F. Enomoto, R. Nado, and M. Sierhuis, "A centralized multi-agent negotiation approach to collaborative air traffic resource management planning," *Proceedings of the AAAI Conference on Artificial Intelligence*, vol. 24, no. 2, pp. 1787–1792, Jul. 2010. [Online]. Available: https://ojs.aaai.org/index.php/AAAI/article/view/18814

[9] J. Rong, S. Geng, J. Valasek, and T. Ioerger, "Air traffic conflict negotiation and resolution using an onboard multi-agent system," in *Proceedings. The 21st Digital Avionics Systems Conference*, vol. 2, 2002, pp. 7B2–7B2.

[10] S. Chae and J.-A. Yang, "An n-person pure bargaining game," *Journal of Economic Theory*, vol. 62, no. 1, p. 86–102, 1994.

[11] M. Bac and H. Raff, "Issue-by-issue negotiations: The role of information and time preference," *Games and Economic Behavior*, vol. 13, no. 1, pp. 125–134, 1996. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0899825696900287

[12] C. Fershtman, "The importance of the agenda in bargaining," *Games and Economic Behavior*, vol. 2, no. 3, pp. 224–238, 1990. [Online]. Available: https://www.sciencedirect.com/science/article/pii/089982569090019Q

[13] M. J. Osborne and A. Rubinstein, *Bargaining and markets*. Bingley: Emerald, 2008.

[14] V. Krishna and R. Serrano, "Multilateral bargaining," *The Review of Economic Studies*, vol. 63, no. 1, p. 61, Jan 1996. [Online]. Available: https://academic.oup.com/restud/article-lookup/doi/10.2307/2298115

[15] C. Murray and G. J. Gordon, "Multi-robot negotiation: Approximating the set of subgame perfect equilibria in general-sum stochastic games," in *Advances in Neural Information Processing Systems*, B. Schölkopf, J. Platt, and T. Hoffman, Eds., vol. 19. MIT Press, 2006. [Online]. Available: https://proceedings.neurips.cc/paper_files/paper/2006/file/ada5e0b63ef60e2239fa8abdd4aa2f8e-Paper.pdf

[16] D. P. Baron and J. A. Ferejohn, "Bargaining in legislatures," *American Political Science Review*, vol. 83, no. 4, p. 1181–1206, Dec 1989. [Online]. Available: https://www.cambridge.org/core/product/identifier/S0003055400088109/type/journal_article

[17] U. Endriss, "Monotonic concession protocols for multilateral negotiation," in *Proceedings of the fifth international joint conference on Autonomous agents and multiagent systems*, 2006, pp. 392–399.

[18] M. Xue, J. Jung, and J. Homola, *Intent Modeling and Conflict Probability Calculation for Operations in Upper Class E Airspace*, 2021. [Online]. Available: https://arc.aiaa.org/doi/abs/10.2514/6.2022-1508

[19] C. Wang, P. Baets, M. Fenkell, A. Tailby, S. Barry, P. Taylor, L. Bouygues, Z. Mian, J. Gentry, and B. Kluttz, "Adaptive risk-based conflict detection for stratospheric flight operations," *Air Traffic Control Association Tech Symposium*, 2020. [Online]. Available: https://videos.atca.org/adaptive-risk-based-conflict-detection-for-stratospheric-flight-operations

[20] M. Korens, S. Gaulden, W. Wei, M. Xue, P. Lee, and J. Silva, "A web-based negotiation tool for conflict resolution in upper-class e traffic management," in *AIAA AVIATION 2024 Forum*, 2024, in press.

APPENDIX

Algorithm 1 Check for Conflict with Inactive Operators

Input: x_i, $conflictPairs$, D
Output: True/False $//True : response, False : propose$
Function Action(x_i, $conflictPairs$, D)**:**
  for $pair$ *in* $conflictPairs$ **do**
    if *(main_operator=*$pair[0]$ ***and*** $pair[1] \in inactiveSet$*)* ***or*** *(main_operator=*$pair[1]$ ***and*** $pair[0] \in inactiveSet$*)* **then**
      return True
    end
  end
  return False

A simple method for determining whether the operator needs to generate a proposal trajectory or a response trajectory. The True output implies an operator needs to generate a response trajectory, whereas the False output means an operator needs to create a proposal trajectory.

Algorithm 2 Multi-Party Flight Trajectory Negotiation

Input: O,F_0,$conflictPairs$
Output: F_p
$AgreementReached \leftarrow$ False
while *not* $AgreementReached$ **do**
  $A \leftarrow O$
  $D \leftarrow \emptyset$
  $F_p \leftarrow \emptyset$
  while *not* IsEmpty*(A) and not exit_round* **do**
    /* Determine if submit a proposal or response based on the conflict status */
    $action \leftarrow$ Action(x$_i$, $conflictPairs$, D)
    if $action$ **then**
      $f_i \leftarrow$ GenerateResponse(x_i, D, F_p, F_0) [20]
      $CR_i \leftarrow$ CalculateResponseCosts(f_i, A, F_0) [20]
      cr = min(CR_i)
      $f^* \leftarrow \arg\min_{f_i \in F_i} CR_i$
      if $cr < rc$ **then**
        $F_p[x_i] \leftarrow f^*$
        Move x_i from A to D
      end
      else
        if *accept* **then**
          $F_p[x_i] \leftarrow f^*$
          Move x_i from A to D
        end
        else
          exit_round = True
        end
      end
    end
    else
      $f_i \leftarrow$ GenerateProposal(x_i, F_0) [20]
      $CP_i \leftarrow$ CalculateProposalCosts(f_i, A, F_0) [20]
      if $\forall cp : cp \in \mathcal{CP}_i, cp > rc$ **then**
        $f^* \leftarrow \arg\min_{f_i \in F_i} CP_i$
        $F_p[x_i] \leftarrow f^*$
        Move x_i from A to D
      end
    end
    if IsEmpty*(A)* **then**
      $AgreementReached \leftarrow$ True
    end
  end
end
return F_p