Negotiation Model for Cooperative Operations in Upper Class E Airspace

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***Abstract*—This work proposes a negotiation model, built upon the sequential bargaining model, for strategic planning among high-altitude operations. The definition of cost/utility, the setup of time-dependent required cost, and the detailed negotiation structure and process are developed. The sensitivities of negotiation strategies or preferences, response time, and limited maneuverability are investigated to understand the behavior of the proposed negotiation model. Results show that the proposed model can serve the cooperative operation concept well: first, this model ensures an agreement can be reached within a predefined time window; second, operators can accurately express their priorities without exposing their private business information; third, the model encourages short response times and helps the negotiation process converge; finally, the limited and unbalanced maneuverability was found less of a concern for a fair negotiation due to the long lead time available for strategic planning.**

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

I. Introduction

To enable efficient and safe operations of new-entrant vehicles and to alleviate the potential burden on air traffic controllers, the concept of Unmanned aircraft systems Traffic Management (UTM) [1]–[5] explored a different approach requiring cooperative operations among operators/pilots through operational intent sharing and coordination. This concept has been extended and proposed by the community to handle traffic management for high-altitude operations. While the concept and basic system were tested in UTM, there are still many critical capabilities needed for high-altitude operations, such as how to share the airspace and resolve potential conflicts between the operational intents of vastly different vehicles.

There is a consensus in the community on developing certain flight rules like existing Instrument Flight Rules (IFR) and Visual Flight Rules (VFR) for new-entrant vehicle operations. Therefore, should any potential conflict happen, operators can resolve it based on the new flight rules. The envisioned new flight rules have been referred to as community-based rules [6], digital flight rules [7], or automated flight rules [8] depending on the circumstances. In addition to these flight rules, both the UTM strategic deconfliction concept [2] and the Cooperative Operating Practices (COP) concept [9] propose a negotiation capability as a complementary means for resolving conflicts during the strategic planning phase. However, no studies have been conducted on how to structure and formulate such a negotiation capability. This work develops a negotiation model that can meet the need for upper Class E traffic management and can be extended to other new-entrant operations as well.

This paper begins with a background of negotiation models. Section III discusses the scope of negotiation for this specific work. Section IV introduces the negotiation model, rules, and procedures. Section V briefly describes the flight replanning algorithm used in the negotiation experiments. Section VI presents experiments and the sensitivity studies of key variables in the negotiation model. Section VII concludes this work.

II. Background in Negotiation

Negotiation or bargaining problems, where two parties whose interests are neither completely opposed nor completely coincident, have been studied in Game Theory since 1950s [10]–[14]. In Game Theory, the negotiation process is formulated mathematically with the minimum quantity of information such that the process can be investigated, proper rules can be defined, and better agreements can be reached. Game Theory has been widely used in many fields, including but not limited to economics, political science, computer science, and statistics.

There have been a number of studies investigating game-theoretic solutions to air traffic conflict management using non-cooperative [15] and cooperative [16], [17] approaches. Non-cooperative approaches ensure separation in worst-case scenarios where no negotiation between agents occurs. Cooperative approaches involve negotiation between agents utilizing incremental bargaining where offers and counter-offers are exchanged through a common protocol.

In the cooperative approaches [17]–[19], two different models are typically applied. Menon et. al. [18] used the static negotiation model: operators are assumed to generate a full list of candidate flight plans associated with scores, and share them to form a utility matrix. From this utility matrix, Nash Equilibrium can be identified. Then a solution is selected from the Nash Equilibrium. Since the utility matrix is static and the number of candidate flight plans is limited, there will be unnecessary extra deviation due to the discontinuous candidate flight plans. Therefore, this type of model is neither efficient nor flexible for conflict management in strategic planning. Pritchett [16] developed a negotiation model based on the sequential bargaining model for tactical conflict resolution among air traffic. Revised trajectories in six dimensions (left, right, up, down, slow, and fast) are required, and time constraints are used to ensure the negotiation process can finish within a given number of steps. Our previous work [20] investigated the sequential bargain model for high-altitude operations, however, the focus was mainly on the conflict-free trajectory optimization given the high-altitude vehicle dynamics.

III. The Scope of Negotiation

Understanding the application scope of negotiation in high-altitude operations is important before developing a negotiation model. Fig. 1 presents a notional timeline using an example encounter scenario between a High-Altitude-Long-Endurance (HALE) fixed-wing aircraft and a high-altitude airship. As shown in the figure, both vehicles are sharing their operational intents formulated based on their flight plans, flight performances, and wind uncertainties [21]. Assuming that the conflict probability of operational intents between these two operations is predicted to reach an unacceptable level at some future time T_x (shown as the red crossing mark), the latest time T_0 for any vehicle to maneuver to avoid the conflict can then be identified [22]. When two vehicles have different performances, the latest times for them to maneuver to avoid the conflict will be different (shown as T_0 and T_0' respectively). For example, in this sample scenario, the airship requires longer lead time than the HALE fixed-wing aircraft. The strategic conflict management phase, which is usually defined to end some time before T_0, consists of a negotiation phase [23] (between T_N and T_F) and a "fallback" conflict management phase (between T_F and T_0).

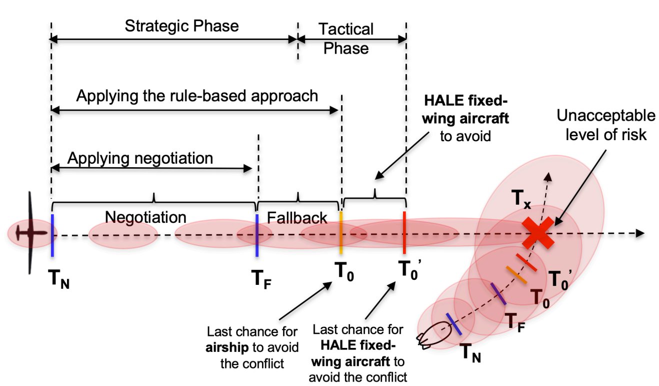

Fig. 1. Timeline in Conflict Management

As shown in Fig. 1, a rule-based approach can be applied through the entire conflict management period, whereas the negotiation model will only be applied during a predefined negotiation time window (between T_N and T_F as shown in the figure). The negotiation takes place during strategic planning, which includes both pre-departure planning and in-flight re-planning as long as the re-planning happens long before any potential conflict occurs (e.g. $>$ 10 or 20 minutes before T_x). The goal of negotiation is not to replace or compete with the rule-based approaches (e.g. the community-based rules) in conflict management. Rather, it is developed to complement rule-based approaches by providing more flexibility and an extra option, such that the operators can chose more efficient solutions based on dynamically-changing operational needs at the moment. The negotiation model is expected to provide an efficient means for operators to share their needs and exchange dynamically-updated operational intent information through the process, such that the operators can achieve better efficiency without sacrificing critical needs. For instance, when there is an unacceptable level of risk between a high-altitude airship and a HALE fixed-wing aircraft as shown in Fig. 1, the community-based rules may require the HALE fixed-wing aircraft to yield the right of way to the airship. However, a negotiation model can help operators find a different but more efficient resolution: if the airship operator thinks that adjusting its heading won't affect the mission (e.g. providing communication services to the ground), the operator probably will agree to yield the right of way to the HALE fixed-wing aircraft.

IV. Negotiation Model

In this work, a negotiation model is developed based on Rubinstein's sequential bargaining model [12] for strategic conflict management in high-altitude operations. The following sections describe the details of this model including definitions of key metrics and parameters, requirements, and procedure.

A. Cost and Utility

Utility is a standard terminology used to measure the value of an action (or a proposed action) in a negotiation model. Since *Cost* is usually easy to understand in conflict management, this subsection starts from the definition of *Cost*, and then a simple function will be introduced later to map between *Utility* and *Cost*.

To help understand *Cost* defined in this work, Fig. 2 presents the same encounter scenario, where f_{h0} and f_{a0} represent the original flight plans for the HALE fixed-wing aircraft and airship, respectively. Due to the uncertainty in future positions, the mean closest points of approach are predicted to be $\bar{P}_{h,cpa}$ and $\bar{P}_{a,cpa}$ for the HALE fixed-wing aircraft and the airship, respectively. d_{cpa} denotes the distance between these two points. Assuming the original flight plans yield an unacceptable level of risk[1], if the HALE fixed-wing aircraft has the full responsibility to maneuver to avoid any potential conflict, then it needs to revise its flight plan to reduce the collision risk to zero. The resultant flight plan is then called

[1] As mentioned before, operational intents that are generated based on flight plans, flight performances, and wind uncertainties are actually used to compute the collision risk. For simplicity, "flight plans" and "operational intents" are used interchangeably here.

the *response flight plan*, represented as ${f_h}^r(f_{a0})$ in Fig. 2, as it is associated with the airship's original flight plan f_{a0}. The new mean closest points of approach will be changed to $\bar{P'}_{h,cpa}$ and $\bar{P'}_{a,cpa}$ with an updated distance d'_{cpa}.

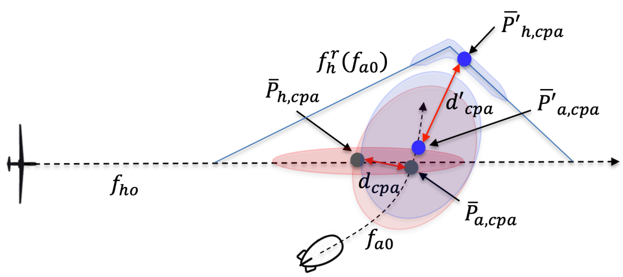

Fig. 2. Cost Definition

The cost of the original flight plan, $Cost(f_{h0})$, is set to zero, and the cost of any revised flight plan will represent the extra cost compared to the original flight plan. This extra cost can be built upon energy, time, or other business-related cost, such as reduced custom coverage when providing communication services, or low charging efficiency for solar-powered vehicles. Allowing costs other than energy and time provides the operator with the flexibility to measure their needs, which is important to high-altitude operations.

To protect sensitive business information, a normalized cost is used. The normalized cost of a flight plan f_h is defined as the ratio between its cost and the cost of the response flight plan as in Eqn. 1.

$$c(f_h) = \frac{cost(f_h)}{cost[{f_h}^r(f_{a0})]} \tag{1}$$

In this work, the cost $c(f_h)$ is required to monotonically increase with the distance between two closest points of approach as in Eqn. 2 with $c(f_h)$ in the range of $[0, 1]$. To ensure that the negotiation process moves closer to an agreement every round, the cost $c(f_h)$ just needs to increase every step.

$$c(f_{h,i}) \geq c(f_{h,j}) \iff d_{cpa,i} \geq d_{cpa,j} \tag{2}$$

In Game Theory, *Utility* is widely used to measure the preference of the negotiator for a given action, and a high *Utility* is always desired. Based on the definitions, a simple function can be defined to map the *Utility* $u(f_h)$ to the *Cost* $c(f_h)$, where $u(f_h)$ is between zero and one.

$$u(f_h) = 1 - c(f_h),\ 0 \leq u(f_h) \leq 1. \tag{3}$$

B. Operator Preference or Strategy

To be more generalized, the distance between two closest points of approach d_{cpa} between two flight plans is further generalized to a normalized deviation $\bar{\delta}$ as shown in Eqn. 4, where the normalized deviation for the original flight plan is defined as zero ($\bar{\delta}(f_{h0}) = 0$) and the response flight plan with full responsibility is one ($\bar{\delta}[{f_h}^r(f_{a0})] = 1$).

$$\bar{\delta}(f_h) = \frac{d_{cpa}(f_h) - d_{cpa}(f_{h0})}{d_{cpa}[{f_h}^r(f_{a0})] - d_{cpa}(f_{h0})} \times 100\%,\ \bar{\delta} \in [0, 1]. \tag{4}$$

Now, the cost will monotonically increase with the normalized deviation as well, whereas the utility will monotonically decrease with the normalized deviation:

$$c(f_{h,i}) \geq c(f_{h,j}) \iff \bar{\delta}(f_{h,i}) \geq \bar{\delta}(f_{h,j}) \tag{5}$$

$$u(f_{h,i}) \leq u(f_{h,j}) \iff \bar{\delta}(f_{h,i}) \geq \bar{\delta}(f_{h,j}) \tag{6}$$

In this work, during the negotiation process, the normalized deviation $\bar{\delta}$ is required to increase every step for each operator. Specifically, $\bar{\delta}$ is required to be proportional to the elapsed negotiation time. The relationship between the utility/cost and the normalized deviation essentially reflects the operator's preference and forms the negotiation strategy, which can be defined before negotiation as a guidance by the operator or analyzed after negotiation based on the negotiation history.

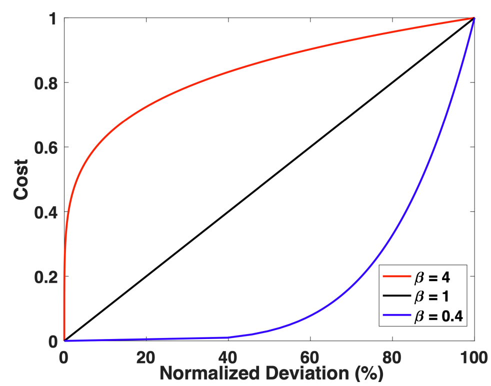

Fig. 3. Three Types of Negotiation Strategy

$$c(f_h) = \bar{\delta}^{1/\beta} \tag{7}$$

Fig. 3 shows three sample negotiation strategies [14] based on the relationship between the cost and normalized deviation (as shown in Eqn. 7): Boulware ($\beta \gg 1$, in red), Conceder ($\beta \ll 1$, in blue), and Linear ($\beta = 1$, in black). The Boulware strategy doesn't deviate much from the original flight plan until the negotiation time is almost exhausted, whereas the Conceder strategy gives in quickly in terms of deviation. The Linear strategy behaves somewhere between Boulware and Conceder.

The operator preference or strategy curve reflects the negotiator behavior, no matter if the strategy is decided by objective business costs, or subjective characteristics, or a combination of both objective and subjective factors. Because the goal of this negotiation model is to provide an efficient way for operators to share their needs, it's assumed that both parties want to find a reasonable and flexible solution that is better than the fallback solution. Thus, operators are expected to construct their strategy curves based on objective business costs; however, it is not guaranteed unless operators are willing to share their private business information.

Separation requirements are often represented by cylinders (or "hockey pucks") in vertical and horizontal dimensions, which are usually uncorrelated. The normalized deviation should have these two dimensions as well, so that the normalized deviation becomes a generalized parameter that can connect any types of maneuvers as long as they can compensate each other in the same dimension. For instance, heading change, speed change, or combined heading and speed change can all contribute to increase the minimum horizontal separation between two flight plans[2]. And climbing, descending, or other combinations can contribute to the vertical deviation.

With the normalized deviations, the maneuver in the response flight plan doesn't need to be the same type as the one in the proposed flight plan, as long as they are in the same dimension (vertical or horizontal). Using the normalized deviation, there is no need to propose and respond in six dimensions (turning left, turning right, speeding up, slowing down, climbing, and descending) as requested in Pritchett's work [19]. The horizontal and vertical deviations are independent from each other in conflict resolution. There is not much to negotiate if one vehicle can only maneuver vertically and the other can only maneuver laterally, because the operators can only choose between full responsibility and zero responsibility[3]. Thus, proposing and responding in two dimensions—lateral and vertical—would be sufficient. In this work, the operator is only required to propose in one dimension, and the second dimension is optional.

C. Time-dependent Required Cost

Rubinstein [12] introduced time constraints to ensure the negotiation results in an agreement by the deadline. There are two types of costs in Rubinstein's model: fixed bargaining cost (by adding a cost at each round) and fixed discounting factor (by multiplying a factor at each round).

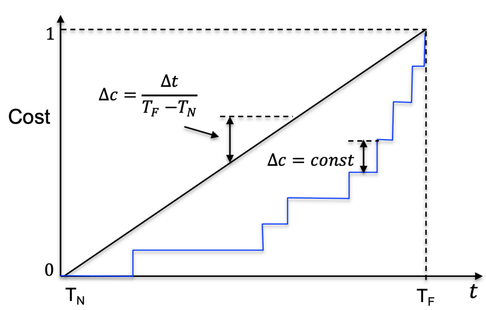

Fig. 4. Time-dependent Required Cost

Pritchett et. al. [19] used a fixed bargaining cost to guarantee that the negotiation can be concluded within a fixed number of steps. Since Pritchett's work focused on tactical conflict resolution, the response time, which refers to the time spent receiving and evaluating a proposal and proposing and sending a new proposal, wasn't taken into account. For strategic planning in high-altitude operations, the communication and vehicle control response times could be long and may vary among different vehicles and operators. A fixed additive bargaining cost would essentially penalize quick responses and favor slow responses (shown as the blue curve in Fig. 4).

$$\Delta c = \frac{\Delta t}{T_F - T_N} \tag{8}$$

$$c_{req}(t) = \frac{t - T_N}{T_F - T_N} \tag{9}$$

To construct a fair negotiation process, a time-dependent additive cost is proposed as in Eqn. 8. Then the *Required Cost* at any time t, $c_{req}(t)$, will increase proportionally to the time used (Eqn. 9). The *Required cost* will be imposed every time when a negotiator proposes a flight plan/operational intent, which means that the cost of the proposal must be greater than or equal to the *required cost* at the moment. This will incentivize quick responses and penalize slow ones and help construct a fair negotiating process.

D. Negotiation Work Flow

Once the terms critical to negotiation are defined, the work flow of the sequential bargaining negotiation is as follows:

- If the predicted conflict risk exceeds a threshold and the current time is within the defined negotiation time window between T_N and T_F, then move to Step 1 and the negotiation starts.
- Step 1: Operator A calculates response operational intents (or flight plans) and associated costs, given the operational intents from Operator B.
- Step 2: Operator A checks the response cost against the *Required cost*. If there are multiple response costs then pick the minimum cost. If it's less than or equal to the *Required Cost*, then an agreement is reached, jump to Step 7. Otherwise, go to Step 3.
- Step 3: Operator A proposes revised operational intents and makes sure their costs are higher than or equal to the *Required Cost*.
- Step 4: Operator B calculates response operational intents and associated costs given the proposed operational intents from Operator A.
- Step 5: Operator B checks the response cost against the *Required cost*. If there are multiple response costs then pick the minimum cost. If it's less than or equal to the *Required Cost*, then an agreement is reached, jump to Step 7. Otherwise, go to Step 6.
- Step 6: Operator B proposes revised operational intents and makes sure their costs are higher than or equal to the *Required Cost*, then go to Step 1.
- Step 7: An agreement is reached, the final proposed and response operational intents are then finalized and submitted.

Fig. 5 presents the negotiation loop, within which the *Required Cost* or Time-dependent cost requirement steadily

[2]It should be mentioned that climb with non-zero horizontal speed can also change the horizontal separation.

[3]The vertical maneuver here refers to a 90° climb or descent with zero horizontal speed

increase with the normalized deviation (essentially with the elapsed negotiation time).

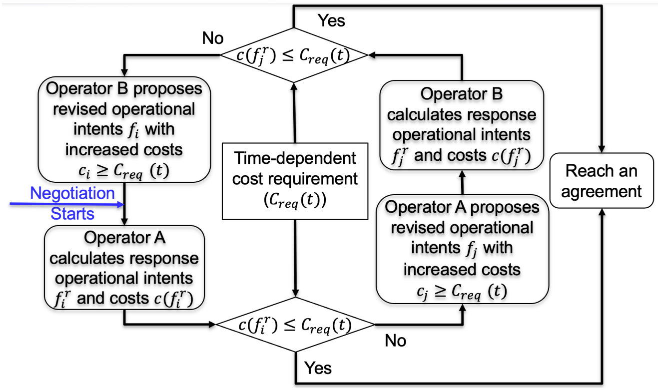

Fig. 5. Negotiation Flow

E. Recap of Core Negotiation Requirements

Core negotiation requirements for this work are summarized below:

- The operators **should** construct their strategy curves or preferences based on their objective business costs.
- The operators **must** propose revised flight plans or operational intents with corresponding costs higher than the time-dependent *Required Cost* defined by Eqn. 9.
- The time-dependent *Required Cost* **must** monotonically increase with the normalized deviation defined by Eqn. 4 and Eqn. 6, which is set to be proportional to the elapsed negotiation time.

V. Flight Replanning Algorithm

In order to perform experiments for the negotiation model, a flight replanning algorithm is needed. However, it should be noted that the negotiation model and its performance should be consistent regardless of the flight replanning algorithm.

To develop a flight replanning algorithm for high-altitude operations, two functions are required: a function to adjust the flight plan to ensure its minimum four-dimensional distance to another flight plan is higher than a given value, and a function to adjust the flight plan such that the risk or probability of conflict [4] with another flight plan does not exceed a specified maximum risk level.

In this work, the first function was built based on the geometric conflict resolution algorithm developed by Bilimoria [24]. Because Bilimoria's algorithm was developed for tactical conflict resolution with only a single flight segment involved, improvements were made to extend it to multiple-segment flight plans. This function will be utilized to revise a flight plan and meet any given minimum distance requirement. For the second function, a simple bisection method was added as the outer loop of the first function to tune the minimum distance to find the zero-risk flight plan. To calculate the probability of conflict intent, the algorithm developed in previous work [21] was applied. Finally, a flight replanning algorithm consisting of the first and second functions was used in the experiments.

[4]The separation standard hasn't been defined for high-altitude operations, however, to enable this study, a 5-nautical mile separation were used.

VI. Experiments and Analysis

Experiments are conducted to illustrate the negotiation process and perform sensitivity analysis to examine possible behaviors associated with this negotiation model.

A. Baseline Example

An example is presented to delineate the negotiation process and to be used as a baseline for sensitivity studies in following subsections. In this scenario, two Global Hawk fixed-wing aircraft are negotiating to mitigate some undesired risk of conflict. Both vehicles are assumed to fly at 340 knots (air speed) and wind is southwest with a mean value of 20 knots and std. of 5 knots. The conflict probability/risk is predicted to reach 54% at 41 minutes from now and exceed 5% at 40 minutes from now, using the algorithm developed in previous work [21].

TABLE I
Scenario Parameters

Parameters	Values
Risk threshold for negotiation	5%
Time to undesired event (T_x)	40 min.
Negotiation time window (min)	[T_x-43, T_x-13]
Response time for both operators	3.0 min
Preference for both operators	$\beta = 4$ (Boulware)
Maneuverability (Operator 1)	Heading change within $[-60°, 60°]$
Maneuverability (Operator 2)	Heading change within $[-60°, 60°]$

Table I lists parameters used in this negotiation scenario. The threshold of risk to trigger the negotiation is set to be 5%, the beginning time of the negotiation window T_N is 43 minutes before the potential conflict at T_x and the ending time of the negotiation T_F is 13 minutes before T_x. The response times for both operators are 3 minutes. The response time refers to the time needed for receiving and evaluating a proposal and proposing and sending a new proposal every time. In addition, both operators' preferences are set to be Boulware with $\beta = 4$. Because the risk exceeds the defined negotiation threshold and current time is in the negotiation time window, a negotiation process will be initiated.

Fig. 6 presents operators' preferences (or negotiation strategies) developed based on their own business costs (shown as the blue and red curves). At each round, the proposed cost is shown as a dot and the evaluated response cost is represented by a square. The required cost at each round is shown as the dashed line segment attached with the proposed cost. The blue color represents the costs for Operator 1 and the red color represents the costs for Operator 2.

Fig. 7 depicts the flight plan proposed by Operator 1 in black dashed line, which is hard to see because not much deviation is offered based on Operator 1's preference setting. Operator 2 evaluates his/her response flight plan (shown as blue dashed

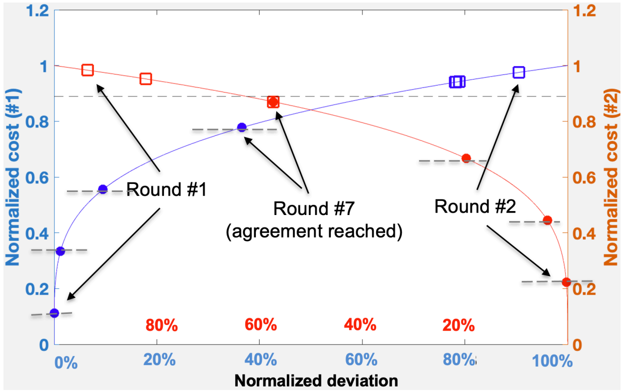

Fig. 6. Proposed, response, and required costs at each round

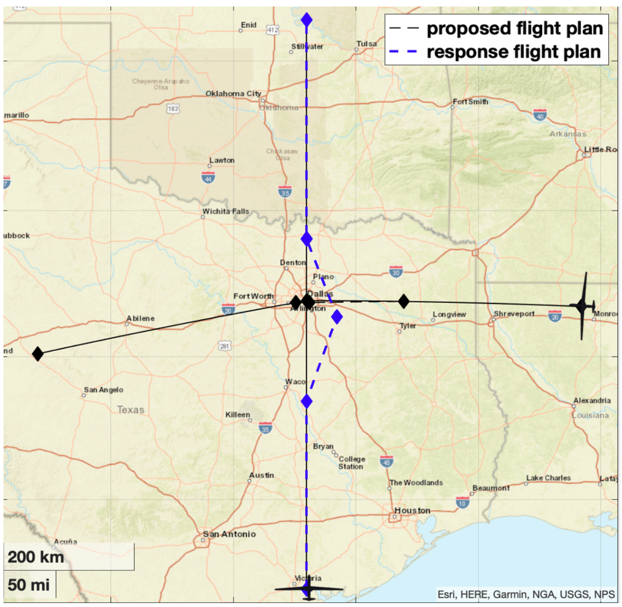

Fig. 7. Round One

curve) with a cost close to one, shown as the red square at the top left corner in Fig. 6. Operator 2 thinks that the response cost is too high, so it decides to propose a revised flight plan (the black dashed line shown in Fig. 8) at a much lower cost of 0.2 (shown as a red dot at the bottom right corner in Fig. 6).

This process continues until Round Seven (Fig. 9) when Operator 2 finds out that his/her response cost will be lower than the required cost (long dashed line in Fig. 6). Operator 2 accepts Operator 1's offer, then an agreement is reached (shown as a red dot enclosed by a red square in Fig. 6). This figure also shows that, in this final agreement, Operator 1 takes 37% of the deviation compared to the deviation needed when Operator 1 has the full responsibility to avoid the conflict, while Operator 2 takes 57% of the deviation compared to the deviation needed when Operator 2 resolves the conflict alone. It is noticed that by sharing responsibility, the sum of the normalized deviation is 94%, which is less than 100% when only one party is responsible to resolve the conflict. Sharing

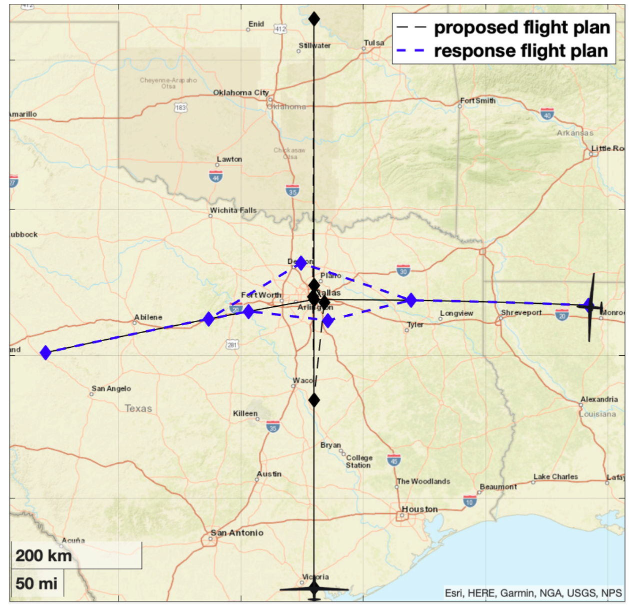

Fig. 8. Round Two

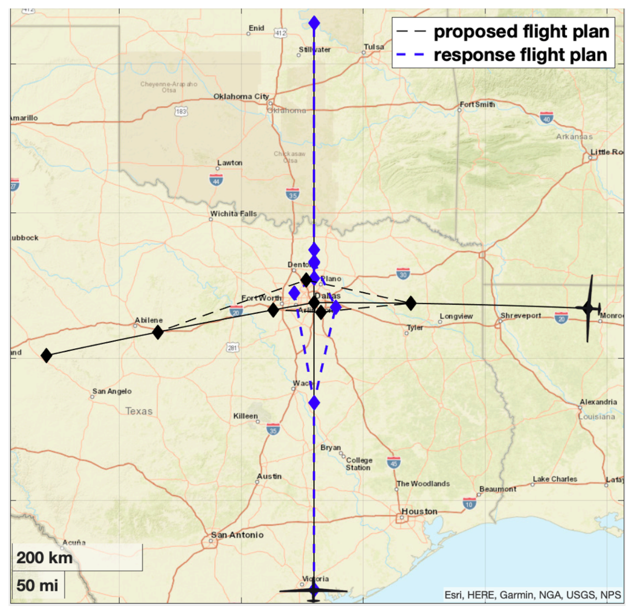

Fig. 9. Final Round

responsibility through negotiation helps improve efficiency.

B. Sensitivity analysis

This section performs sensitivity analysis for three key variables in this negotiation model: operator preference, operator response time, and vehicle maneuverability. To simplify the description, in this section Boulware means $\beta = 4.0$, Linear refers to $\beta = 1.0$, and Conceder represents $\beta = 0.4$. Unless specified differently, the default settings are the same as the baseline in the previous section.

1) Impact of Operator Preference: To investigate the impact of operator preference on the outcome of the negotiation, five different pairs of operator preference were tested: Boulware to Boulware, Boulware to Linear, Boulware to Conceder, Linear to Linear, and Linear to Conceder (as shown in Table II). These five cases were further tested with two different response times: three minutes and one minute.

TABLE II
TEST SCENARIOS FOR OPERATOR PREFERENCES

Case	Operator A preference	Operator B preference	Response time (min)
I	Boulware	Boulware	3.0
	Boulware	Boulware	1.0
II	Boulware	Linear	3.0
	Boulware	Linear	1.0
III	Boulware	Conceder	3.0
	Boulware	Conceder	1.0
IV	Linear	Linear	3.0
	Linear	Linear	1.0
V	Linear	Conceder	3.0
	Linear	Conceder	1.0

Fig. 10 presents negotiation results using the normalized deviation pairs from the final agreements. The cases with 3-minute response times are shown in blue and the remaining five cases with 1-minute response times are shown in green. As a reference, the red dashed line segments represent the theoretical splits, where the two preference curves intercept with each other.

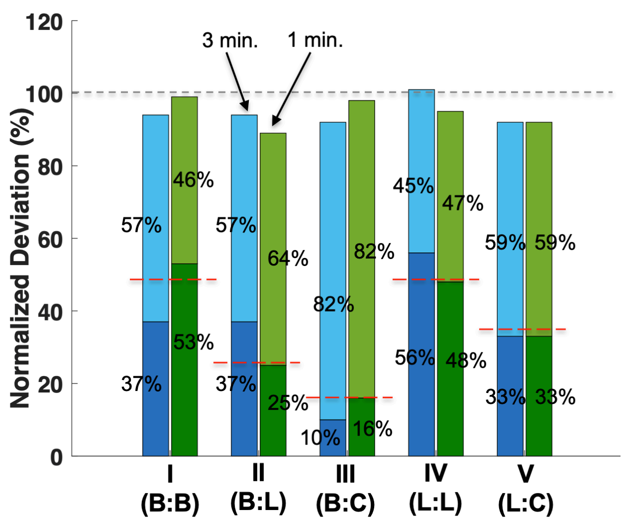

Fig. 10. Sensitivity of Preference

It comes at no surprise that higher β values (or a stronger preference for small deviation) result in less deviation when two operators have different types of preferences (as shown in Case II, III, and V). Whereas, if both operators have the same type of preferences, the results were close to an even split in terms of deviation.

However, it is observed that many resultant splits are slightly different from the theoretical ones, especially when the response time is high (three minutes in this case). One-minute response times help move the final splits closer to the theoretical values, as shown in Fig. 6. Although the operator preferences define the final distribution of responsibility between two operators, the negotiation step size decided by the response time is also important to realize the defined preferences.

In cases where both operators had the same preference, results showed that the operator who started the negotiation first didn't gain any obvious advantage, which suggests the negotiation order (who starts the negotiation first) doesn't bias the outcome.

In addition, it is noticed that, in most of the test cases, the sum of the normalized deviation is less than one, which further shows that negotiation can improve the system efficiency.

2) Impact of Response Time: Previous section showed the impact of the response time when both operators have the same response time. This section will focus on the analysis when two operators have different response times. Table III shows the settings of four test cases.

TABLE III
TEST SCENARIOS FOR RESPONSE TIME

Case	Operator A		Operator B	
	Response time (min)	Preference	Response time (min)	Preference
I	1.0	Boulware	1.0	Linear
II	3.0	Boulware	1.0	Linear
III	5.0	Boulware	1.0	Linear
IV	5.0	Boulware	3.0	Linear

Fig. 11 presents the results with the red dashed line showing the theoretical split for the pair of Boulware and Linear, which is at 26%. The splits for Case I and II are very close to the theoretical value when both operators have response times of 3 minutes or less. When the difference in response times increases further more (as in Case IV) or overall response times are increased (as in Case V), because shorter response times allow finer step sizes when adjusting flight plans or operational intents, the operator with short response time starts to have advantage with reduced responsibility.

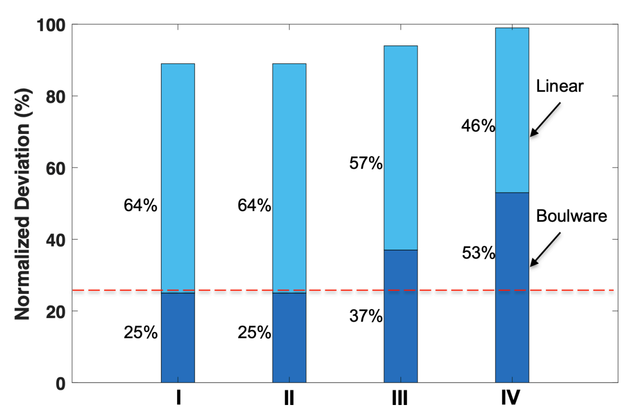

Fig. 11. Sensitivity of Difference in Response Times

In Case III the final split between the operator with Boulware and a 5-minute response time and the operator with

Linear and a 1-minute response time changes to $(37\%, 57\%)$. The benefit of being Boulware was less because of the longer response time. In Case V, that benefit is completely negated and even reversed. With a 3-minute response time, the operator with Linear preference need only contribute 46% in terms of normalized deviation, even less than the operator with Boulware. Short response time brings advantage, and it can even dominate the impact of the preference.

3) Impact of Maneuverability: To study the impact of maneuverability, in this section five cases were tested; the independent variables are presented in Table IV. To focus on the sensitivity of maneuverability, the response time and preference β are set to one minute and 1.0, respectively, to reduce their impacts on final negotiation results.

TABLE IV
TEST SCENARIOS WITH VARIOUS MANEUVERABILITIES

Case	Heading change range		Resolution
	Operator A	Operator B	time (min)
I	$[-60°, 60°]$	$[-60°, 60°]$	$T_x - 13$
II	$[-30°, 30°]$	$[-60°, 60°]$	$T_x - 13$
III	$[-10°, 10°]$	$[-60°, 60°]$	$T_x - 13$
IV	$[-5°, 5°]$	$[-60°, 60°]$	$T_x - 13$
V	$[-5°, 5°]$	$[-60°, 60°]$	$T_x - 23$

Fig. 12 presents the negotiation results. When Operator A's heading change range is reduced from $[-60°, 60°]$ (Case I) to $[-10°, 10°]$ (Case III), splits between the final normalized deviations were remained balanced (e.g. 48% vs. 47% or 48% vs. 45%). Since the resolution started 13 minutes before the potential conflict, the long lead time appears to have compensated for the limited heading change. However, when Operator A's heading-change range is further decreased to $[-5°, 5°]$, Operator A benefited by a smaller normalized deviation (38%) in the negotiated agreement than Operator B (65%), because vehicle's maneuverability is too limited. However, the benefits of poor maneuverability appear to erode with larger resolution time. In Case V, which has a 10 minute longer resolution time, the splits become balanced again $(41\%$ vs. $39\%)$, even though the maneuverability of two operators is drastically different.

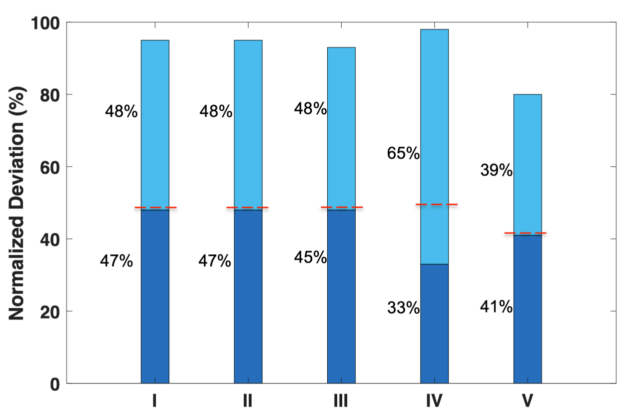

Fig. 12. Sensitivity of limited maneuverability

For negotiation in tactical resolution, past study [19] showed that vehicles with limited maneuverability have an advantage in negotiation over vehicles with better maneuverability. Whereas, in strategic planning, a long lead time can compensate for limited maneuverability. With sufficient time, the vehicle with limited maneuverability can create sufficient separation and even completely resolve the conflict by itself. Therefore, vehicles with limited maneuverability can participate negotiation fairly for strategic planning without much of a problem.

C. Discussion

A couple of observations from the above experiments:

- All negotiation test cases were finished within the defined time window, which shows that the time cost introduced in the negotiation model works as expected.
- Operator's preference determines the final responsibility in conflict resolution, and the theoretical split is at the intercept point between two preference curves. Although an operator can play Boulware to counteract another operator's choice of being Boulware, it is assumed that both operators are willing to cooperate and this negotiation model is developed to help them express their actual needs and facilitate the negotiation process. If an operator is not willing to cooperate with others, it doesn't make sense for him/her to even start the negotiation process.
- Shorter response time helps reduce the negotiation step size and achieve results closer to theoretical splits. When two operators have different response times, the one with the shorter response time has an advantage, and the advantage can counteract the impact of operator preference even if the other operator, who has a longer response time, is "Boulware."
- Limited maneuverability appears to be less problematic for a fair negotiation in strategic planning because the long lead time helps compensate for the effect of limited maneuverability. This characteristics make this negotiation model fit well in the strategic planning.
- In most cases, the sum of the normalized deviations for two operators is less than 100%, which is the value when all the responsibility resides with one vehicle. This demonstrates that negotiation helps improve efficiency.

VII. CONCLUSIONS

Unlike conventional air traffic management, the traffic management of new-entrant vehicles demands cooperative operations among operators with minimum burden on air traffic controllers. Negotiation is intended to complement rule-based approaches (e.g. community-based rules or automated flight rules) and to provide an alternative option for strategic planning.

This work proposed a negotiation model for strategic planning in high-altitude operation, built upon sequential bargaining negotiation. The definition of cost/utility, the setup of time-dependent required cost, and the detailed negotiation process were developed. The sensitivities of negotiation strategies, limited maneuverability, and response time were presented to better understand the behavior of the newly proposed model. The experiments showed that the proposed time cost guarantees that an agreement will be reached by the end of the negotiation deadline. The time cost is designed to encourage short response time during the negotiation and to construct a fair negotiation process. This feature also helps move the negotiation process forward. Experiments reveal that operators can express their actual needs via different preference setup without exposing their private business costs. In strategic planning, the unfair negotiating leverage that stems from limited maneuverability can be neutralized by instituting the long lead time, which makes this negotiation model suitable for a wide range of vehicles with dramatically different maneuverability. Overall, experiments showed that the proposed negotiation model can serve the need of cooperative operation during the strategic planning phase for high-altitude operations.

Future work will focus on the negotiation implementation including optimized interface design to fit actual needs from operators. Evaluation tests in a higher fidelity simulation environment will be conducted to collect feedback from stakeholders to further improve the negotiation model.

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