A Web-Based Negotiation Tool for Conflict Resolution in Upper Class E Traffic Management

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In Upper Class E airspace 60,000 feet (or Flight level / FL600), vehicles such as High Altitude Long Endurance (HALE) balloons and slow fixed-wing gliders have diverse vehicle characteristics and limited maneuverability. Due to these unique characteristics of high-altitude operations, a new type of strategic negotiation-based conflict resolution method has been proposed to avoid potential conflict between vehicles in Upper Class E airspace, well in advance of the conflict point and with ample time for bilateral negotiation. This paper introduces the first real-time web-based negotiation tool for high-altitude operations. To facilitate negotiation, this tool incorporates a bilateral negotiation model with an algorithm to assess conflict risks and generate new flight trajectories with a given flight path deviation. This tool allows users to make decisions during negotiation manually and automatically while enforcing the needed constraints for negotiation to be successful. Operators can make decisions at every step while they interact with each other on separate devices. To conduct sensitivity analysis, a mechanism that automates human inputs to the user interface is also developed for this web-based negotiation tool, such that fast-time simulations can be constructed and used to explore various scenarios to gain insights into this web-based negotiation model. Using this tool, a study was conducted to evaluate the impact of different negotiation strategies, vehicle types, vehicle crossing angles, and operator response times during the negotiations on metrics such as total negotiation completion time, number of negotiation rounds, and extra flight distance to avoid the conflict due to negotiation, compared to ones without negotiation. The results suggest that operators benefit from using negotiated flight paths with quick response times, across various crossing angles and vehicle types. Various Negotiation Strategies are investigated to simulate the behaviors associated with different types of negotiations. The findings demonstrate that, in comparison to the conventional method where a single operator assumes full responsibility, negotiation-based strategic deconfliction reduces the total extra flight distance by an average of 24% - 27%**. On an individual basis, each operator may be able to save an average of** 65% **of their extra flight distance.**

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I. Nomenclature

rc = The required cost constrained by $0 \leq rc \leq 1$.
f_i = A trajectory associated with the ith operator where $i = 1, 2$.
β = The negotiation strategy value for operator i.
$f_{i,0}$ = The original trajectory for operator i.
$f_{i,B}$ = The baseline trajectory for operator i.
$f_{i,P}$ = The proposal trajectory for operator i.
$f_{i,R}$ = The response trajectory for operator i.
δ_i = The normalized flight distance for operator i.
c_i = The cost associated with operator i.

II. Introduction

Upper Class E airspace is defined as 60,000 feet (or Flight level / FL600) in the National Airspace System (NAS). There has been an increase in demand for operations that need to effectively maneuver in this airspace. Ensuring safety for aircraft in Upper Class E has unique challenges because of the vast diversity of aerial vehicle types that are expected to operate in the near future. Such aircraft include supersonic transport vehicles, 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. These vehicles will operate in or pass through Upper Class E airspace [1]. Each vehicle will have different levels of maneuverability, speed, weight, size, flight duration, and control, which will create a unique challenge for these vehicles to engage in conflict detection and de-escalation.

In the anticipation of increased demand for operations in Upper Class E airspace, NASA and the FAA have explored a new concept called Upper Class E Traffic Management (ETM). In the current proposed plan by the FAA, version 1.0 ETM Concept of Operations [2], operations in Upper Class E airspace will need to be cooperative with operators managing and sharing their operational intents with neighboring operators to avoid conflict. There is a consensus in the community that negotiation for strategic deconfliction is the right direction, but there are no specific guidelines for what this might look like.

A negotiation model tailored to meet the needs of ETM vehicles has been developed in previous work [3] to avoid potential conflict between vehicles, well in advance of the conflict point and with ample time for bilateral negotiation. This model assumes that operators are willing to cooperate. Although operational intents need to be shared, the details of an operator's mission, such as true cost, can be kept private. Using principles from game theory, this model can produce equitable conflict-free flight trajectories within minutes. The solution set of conflict-free trajectories found through negotiation is mutually agreed on and equitable since all operators will share the responsibility and absorb partial costs. No single operator will need to take full responsibility and cost. Previous testing of this model has shown that outcomes are based mostly on cost strategy and response times, and are not affected by vehicle maneuverability or who proposes first.

Although the results from prior negotiation model work were positive and promising, it was difficult to interact with the model in real-time, visualizing the negotiation processes step-by-step. To address this problem, we developed a web-based tool with the front-end user interface (UI) in web-based client software and the conflict-detection and trajectory generation algorithms in the back-end, server-side software. The front-end UI allows human operators to interact and negotiate with other operators at each negotiation step, set the negotiation parameters, and visualize the outcome. This implementation allowed the negotiation to happen more realistically – with breaks between proposals and counter-proposals that mirror human decision-making and potential delays caused by distributed web-based tool interactions similar to the ETM concept's possible implementations. An automated testing mechanism was also developed to conduct sensitivity analysis and enable fast-time simulation with this web-based negotiation tool. Various factors that may affect the negotiation process are investigated through different scenarios.

The remainder of this paper is organized as follows. Section III will review previous work on the negotiation model, conflict detection algorithm, and trajectory generation algorithm used in this program. Section IV will describe this program's implementation and Section V will describe the process for automating human interactions required to conduct a sensitivity analysis. Then, in Section VI, the experiment details, such as the input factors and output measures, will be covered. Results and the sensitivity analysis for key parameters that may affect the effectiveness of the negotiation model will be analyzed in Section VII. Key observations from the sensitivity analysis will be described in Section VIII. Concluding remarks and the direction of future work can be found in Section IX.

III. Review of Existing Work

This section reviews the literature on two-party negotiation models and conflict risk assessment and reduction algorithms to understand the individual components of this tool.

A. Negotiation Models for Air Traffic Management

Several two-party negotiation models have been developed in the past for applications in the air traffic management domain. Menon et al.[4] 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 [5] can be identified. Then, a solution is selected from the Nash Equilibrium. Pritchett [6] developed a negotiation model based on the sequential bargaining model for tactical conflict resolution among air traffic. Revised trajectories consisting of heading changes (turn left/turn right), altitude changes (climb/descend), and speed changes (acceleration/deceleration) are required, and time constraints are used to ensure the negotiation process can finish within a given number of steps. Our previous work [3] proposed a negotiation model for strategic planning in high-altitude operations built upon sequential bargaining negotiation. The time-dependent utility is used to guarantee that an agreement will be reached by the end of the negotiation deadline. The flight trajectories are proposed based upon normalized deviation instead of multiple dimensions as in [6], so vehicles with different maneuverability and preference can still negotiate with each other. The definition of the normalized cost ensures that operators can express their actual needs via different preference setups without exposing their private business costs.

B. Conflict Risk Assessment and Reduction Algorithm

Due to the uncertainty associated with high-altitude operations, the intended strategy for assessing the conflict risk between two parties involves measuring the probabilistic chance of conflict. Previous studies have described different methodologies and algorithms to detect conflict. Two papers in particular [7, 8] describe two different methods for assessing conflict probability. The algorithm from previous work [9] leverages a hybrid model to improve the accuracy of conflict risk assessment for turning segments. This algorithm, implemented in our current research, allows the negotiation model to input the flight trajectory plans and vehicle parameters of the involved parties and output a probabilistic likelihood of conflict as a percentage. Once potential conflict has been detected, the next challenge is to minimize the conflict probability down to 0% with a new conflict-free trajectory.

In addition, the negotiation model needs an algorithm that can work in conjunction with the conflict detection algorithm to reduce conflict risk and deviate from the original trajectory. The heading change algorithm, as developed in [10, 11], was employed alongside a bisection algorithm. This combination can then be used to generate a trajectory with a given extra flight distance with reduced conflict risk, or a trajectory with a given conflict risk level. Further research could explore the extension of these methods to incorporate other trajectory maneuvers.

IV. Design and Development of Web-Based Negotiation Tool

In previous research, Xue, Ishihara, and Lee proposed, developed, and evaluated a two-way negotiation model for ETM operations [3]. Although the results were positive and promising, the method could only be tested in a fast-time analysis, and it did not allow a way to interact with the model in real-time, participating in and visualizing each negotiation step. Negotiation models are often implemented and tested in a fast-time analysis [3, 12], in which there is no easy method for generating the interactivity of two operators inherent in the concept of negotiation. In this research, we have developed a web-based tool that addresses the problem by building a user interface (UI) that allows the operators to connect, communicate, and negotiate with each other in real-time.

The tool allows human operators of the impacted vehicle(s) in conflict to access the negotiation model and its parameters interactively in real-time. It has a distributed architecture, with the front-end UI in a web-based client software and the negotiation algorithms and models in the back-end, server-side software. The front-end UI allows human operators to interact and negotiate with other operators at each negotiation step, set the negotiation parameters, and visualize the outcome. This implementation allowed the negotiation to happen more realistically – with breaks between proposals and counter-proposals that mirror human decision-making and potential delays caused by distributed web-based tool interactions similar to the ETM concept's potential implementations. Our negotiation tool comprises functions to facilitate negotiation rules, communication between operators, conflict detection, and trajectory generation. Once this real-time negotiation tool was developed, additional capabilities were built to run the tool in an automated batch mode to test a large set of simulation runs using the same tool built for human-in-the-loop operations. In this section, we will first explain the implementation of the conflict detection and trajectory generation algorithms. Then, we will discuss the overall architecture of the program and the UI design. Lastly, we will explain how the program automated the UI interactions to be used in a fast-time study.

A. Conflict Detection

Given two unique flight trajectories, including latitude coordinates, longitude coordinates, altitude, speed, vehicle type, waypoint tolerance, maximum trajectory deviation, wind profile, and a minimum separation parameter, the negotiation tool calls upon an algorithmic operational intent model, formulated from previous work [7], to simulate trajectories. Using kinematical analysis, the model checks the positioning of the two ETM vehicles every ten simulated seconds and outputs a probabilistic chance of conflict at each instantaneous time; the data are stored in a .json file. Suppose the simulated operational intents take 60,000 simulated seconds to complete. Then, the model will output 6,000 rows of flight track data containing the time every 10 seconds and the likeliness of conflict at each time. The likeliness of conflict is a value that ranges from 0% to 100%, with 100% guaranteeing conflict between the two nominal flight trajectories. The conflict resolution method observes the highest conflict probability in the simulated operational intent and when it occurs, and then reduces the probability to 0%. An example of this could be a peak probability of 80% that occurs 6,000 seconds from departure. By reducing the peak probability from 80% to 0%, a conflict-free flight trajectory consisting of waypoints is guaranteed. Therefore, a conflict-free flight trajectory is defined as the trajectory with a 0% likelihood of conflict throughout an operator's simulated operational intent. This serves as the main basis for calculating new trajectories.

B. Trajectory Generation

The main goal of the trajectory generation system is to produce a flight trajectory with a peak conflict probability of 0%. Utilizing the trajectory generation algorithm from previous work [3], the negotiation tool generates trajectories through a series of input parameters acting as rules by which the trajectory generation algorithm must abide. Figure 1 displays the input parameters into three categories: Operator 1 inputs, Operator 2 inputs, and the negotiation trajectory tool inputs. The individual flight trajectory plans and vehicle details provided by both operators help describe the scenario to the trajectory generation algorithm, while the negotiation tool inputs describe a list of constraints the algorithm must follow. The trajectory generation algorithm will output a conflict-free flight trajectory plan with these parameters defined.

Three unique trajectories exist within the trajectory generation algorithm: baseline trajectories $f_{i,B}$, proposal trajectories $f_{i,P}$, and response trajectories $f_{i,R}$. Each trajectory uses the same trajectory generation algorithm, but the input parameters are differentiated to achieve a distinct type of trajectory output. $f_{i,B}$ assumes 100% maneuver responsibility for one operator and no contribution from the other. $f_{i,P}$ assumes a user-defined maneuver responsibility of less than 100%, while $f_{j,R}$ will ideally contribute to the remaining responsibility left to avoid conflict. In previous work [13], the trajectory generation system utilized only deviation to calculate cost c_i. Deviation measures the closest points of approach (CPA) between a newly generated flight trajectory plan and the opposing operator's original flight trajectory. One of the requirements of that work was that c_i is required to monotonically increase the distance between two CPA points, which ensures that the negotiation process moves closer to an agreement at every round. During subsequent testing in our current research, it was found that deviation did not always meet the requirement of a monotonically increasing cost. To remedy this issue, this paper has added a method to utilize flight distance as an additional layer on top of the deviation algorithm to provide a more intuitive and reliable behavior toward achieving a monotonically increasing cost. Rather than measuring the CPA distance between a generated trajectory and an opposing original trajectory, the flight distance of a generated trajectory is measured instead. Since deviation was used in tandem with cost as a measurement of responsibility usage, it has since been replaced with a method that measures flight distance. The updated terminology in this paper replaces deviation with normalized flight extra distance δ_i and is defined in Eq. (1). The numerator represents the extra flight distance an operator will take from their original flight trajectory plan. The denominator represents the full extra flight distance from their original flight trajectory plan to assume full responsibility. Therefore, the definition of δ_i describes the amount of responsibility an operator inherits to avoid conflict in terms of flight distance.

$$\text{Normalized Extra Flight Distance } (\delta_i) = \frac{\text{Proposal/Response Flight Distance} - \text{Initial Flight Distance}}{\text{Baseline Flight Distance} - \text{Initial Flight Distance}} \tag{1}$$

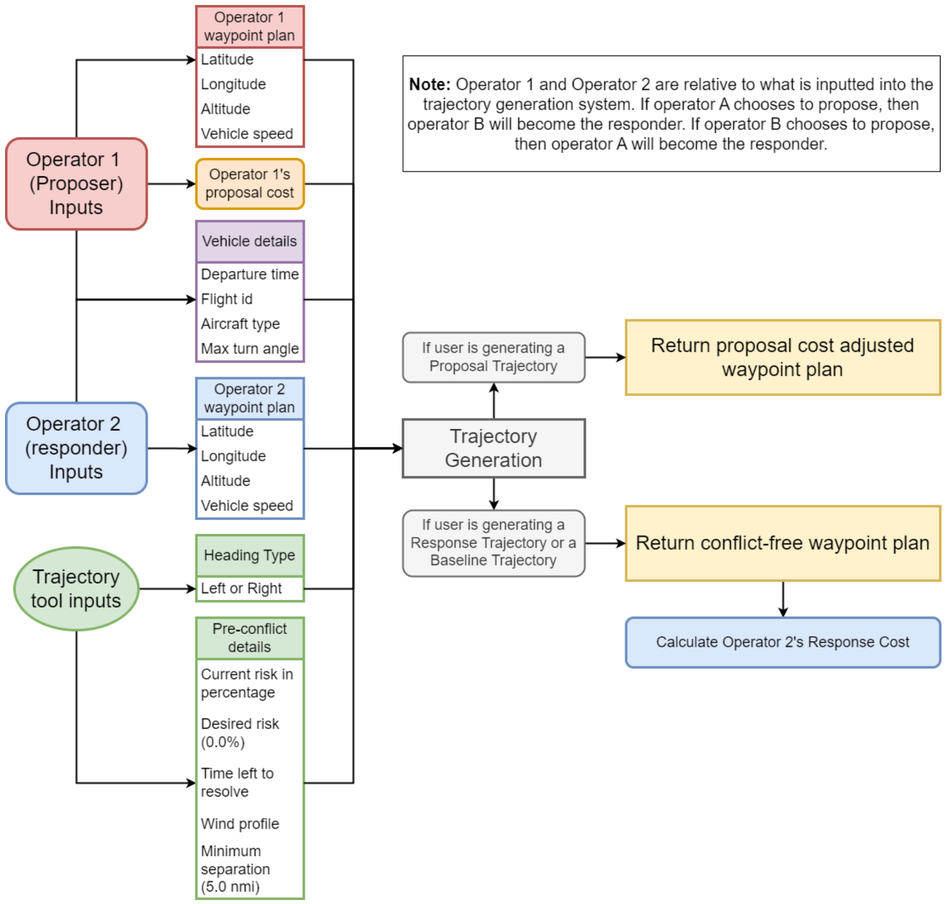

Fig. 1 Overview of the input/output parameters for the Trajectory Generation algorithm.

In the previous studies [3], an operator's Negotiation Strategy was represented as the β value, which reflects the relationship between c_i and deviation. It now reflects the relationship between c_i and δ_i. To briefly recap the behavior of the strategies from previous work, the Boulware strategy, which is represented as $\beta >> 1$, employs a Negotiation Strategy in which an operator is hesitant to maneuver early in the negotiation process from $f_{i,0}$ until the remaining negotiation time is low. The Conceder strategy, which is represented as $\beta << 1$, represents an operator that is much more willing to maneuver from $f_{i,0}$ at the start of negotiation. When $\beta = 1$, the relationship between c_i and δ_i is linear and one-to-one throughout the negotiation process. In this paper, since deviation has been substituted with δ_i, c_i is now defined in terms of extra flight distance, and the Equation that represents the relationship between c_i, δ_i, and β has been updated, as shown in Eq. (2).

$$\text{Cost using Extra Flight Distance } (c_i) = \delta_i^{\frac{1}{\beta}} \tag{2}$$

Suppose an operator's flight trajectory was generated as a proposal flight trajectory $f_{i,P}$. Since $f_{i,P}$ is generated based on a user-defined proposal cost c_i, there is no guarantee that the $f_{i,P}$ will be conflict-free with the opposing operator. To guarantee a conflict-free arrangement, the negotiation model will calculate a response flight trajectory $f_{j,R}$, which takes the opposing operator's original trajectory $f_{j,0}$ and will maneuver in both a left and right turn heading change until $f_{j,R}$ becomes conflict-free with $f_{i,P}$. Using the previous work from [7], we can determine whether $f_{i,P}$ and $f_{j,R}$ are conflict-free with each other. The negotiation tool undergoes an iterative process of resolving conflict by calculating the peak probability of conflict between the two flight trajectories. If the peak probability of conflict is greater than 0%, then the heading turn angle needed to generate $f_{j,R}$ increases until it becomes conflict-free with $f_{i,P}$. If the peak probability is 0%, then there is no need to run the trajectory generation algorithm again since the responder's $f_{j,R}$ is already conflict-free with $f_{i,P}$. The iterative process ends when both $f_{i,P}$ and $f_{j,R}$ are conflict-free, and only in that condition a response cost can be calculated.

C. Architecture Design

The client can interact with the program through its web user interface, as indicated in the Architecture Design diagram in Fig. 2. All information are displayed to users, who can control the program by interacting with the interface. To achieve this in a web-based setting, each client starts a two-way WebSocket channel [14] with the Python server on which the negotiation model is based and makes REST API [15] calls to that server. The Python server handles the negotiation model's data generation and management components, such as conflict detection, data storage, and trajectory generation. The REST API helps facilitate communications between the client and server. Logic is held for each part of the program in their modules, as shown by Fig. 2. Due to the small amount of data needed for this program, the data are stored in a file system that can be directly accessed through read-write operations.

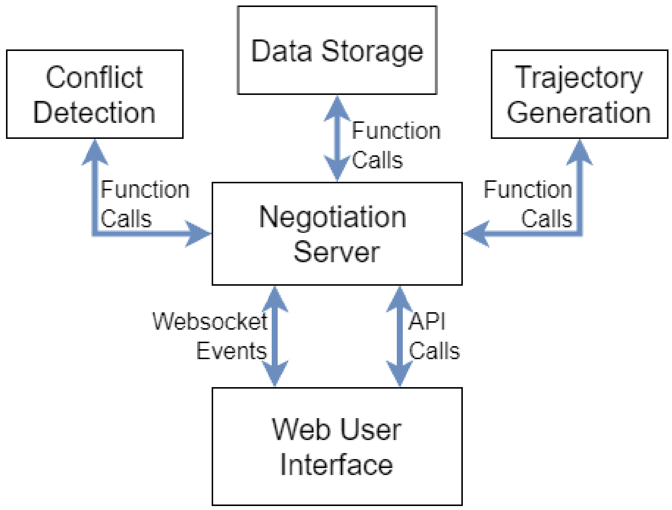

Fig. 2 Simple architecture design diagram for the negotiation tool.

D. Design of User Interface

To briefly walk through the UI, once two operators load into the program, they will be greeted with an initial setup, where each operator can input their username, conflict group, flight trajectory, and Negotiation Strategy as shown in Fig. 3. The conflict group is used for internal testing purposes, which can be ignored in this paper. Once both operators finish entering their initial inputs and click on "Submit Operation," the UI will send their information to the Negotiation Server to check for conflict. If conflict is detected, a popup alert will appear to the operators indicating that conflict exists, and a prompt to begin negotiation will appear. During negotiation, relevant conflict information will appear on the right side of the screen, as shown in Fig. 4, which displays the amount of time until the undesired event happens, the required cost, the conflict peak probability, and an overview map that contains both operator's $f_{i,B}$ and $f_{i,0}$.

Whoever proposes first will be greeted with a proposal UI as shown in Fig. 5 that allows the proposing operator to enter their c_i. As shown in the Figure, the proposing operator can use a slider or type in their cost value, and the program will automatically apply their Negotiation Strategy β value to calculate δ_i. Once the proposal cost is submitted, the trajectory generation algorithm is called, and it calculates $f_{i,P}$ based on the proposer's desired δ_i value. The user is presented with a graph displaying their $f_{i,P}$, as shown in Fig. 6, which the proposer can review before sending the trajectory to the other operator.

Once the proposing operator sends their $f_{i,P}$, the responding operator will receive the same graph as displayed in Fig. 6. The responding operator can generate a response trajectory by clicking on the "Generate Response" button. The UI will call the trajectory generation algorithm to generate $f_{j,R}$ and its c_j. After this process, $f_{i,P}$, $f_{j,R}$, $f_{i,0}$, $f_{j,0}$, and c_j are displayed as shown in Fig. 7. Based on the information displayed in the Figure, the responding operator can choose to either click on "Accept" or "Decline" based on their personal choice. If "Decline" is clicked, then a new negotiation round begins with both operators' roles being swapped. The responding operator becomes the proposer, and the proposing operator becomes the responder. Each new cycle begins with asking the proposer to enter a cost within the proposal UI, and the cycle of proposing and responding continues until an operator clicks on "Accept," which ends the negotiation with both operators receiving a mutually agreed upon conflict-free flight trajectory.

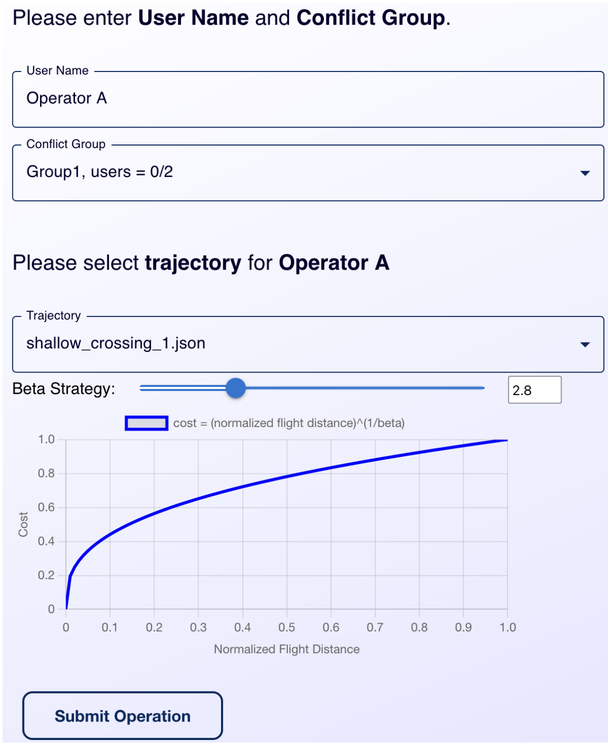

Fig. 3　Setting up a conflict scenario for testing.

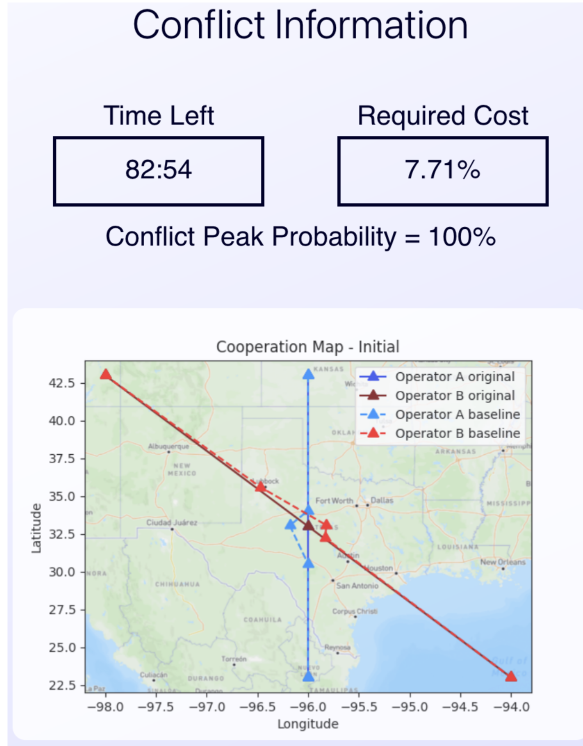

Fig. 4　The conflict information is displayed throughout the negotiation after the conflict is detected.

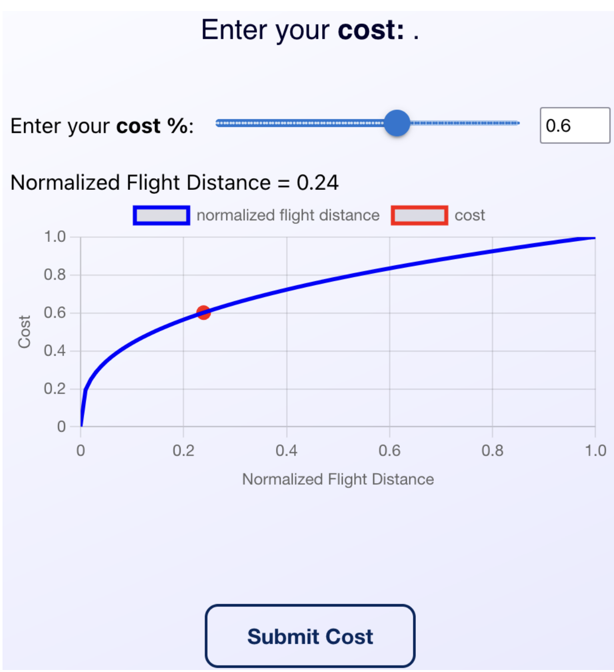

Fig. 5　The UI to enter the cost of a proposal trajectory.

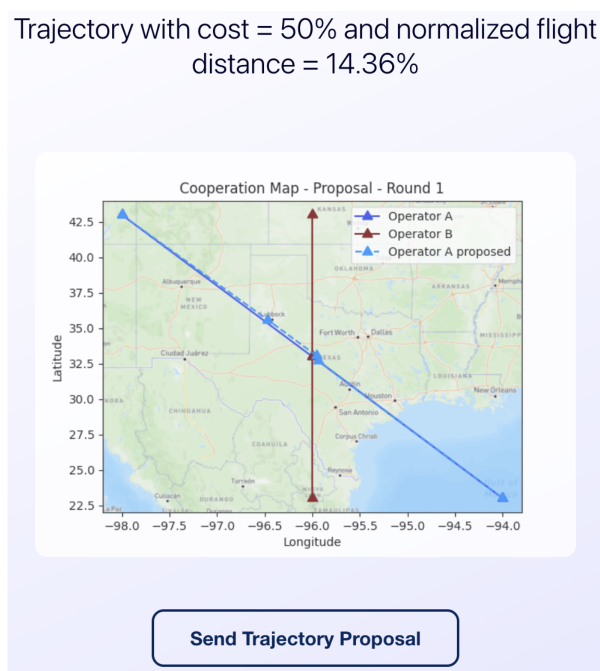

Fig. 6　The Proposal Trajectory UI.

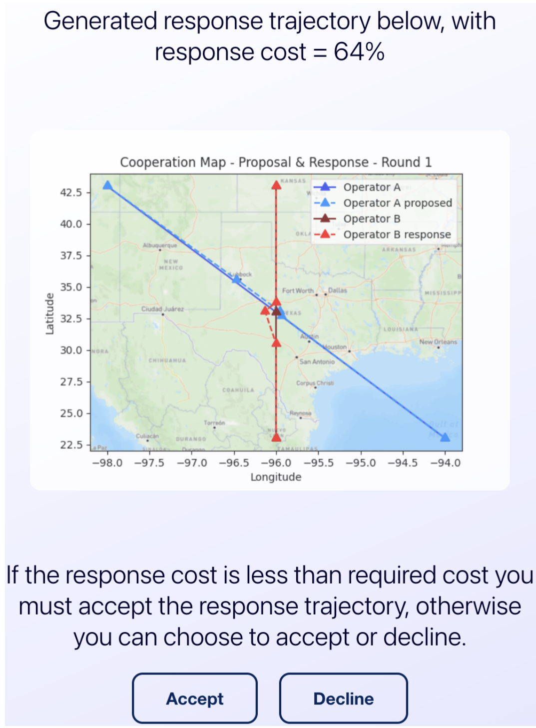

Fig. 7 The Response Trajectory UI.

V. Automating Human Interactions

The web-based negotiation tool provides a framework for allowing interactions between human operators and the negotiation algorithm through a web-based user interface that allows the users to visualize the proposed flight trajectories and modify the negotiation parameters in real-time. There are also natural delays in proposal/response interactions, which affect the overall solutions in ways that were not simulated in previous fast-time implementations.

However, the tool architecture created run time challenges to perform batch runs that may take a long time to complete but are needed to explore different negotiation strategies or run sensitivity analyses of the impact of different input conditions on the overall strategies. In this research, an automation system was developed to create a controlled environment, allowing different input factors to run sequentially in a batch setting. With the current design of the tool, each experimental run can range from 30 minutes to nearly two hours, and a batch run for a given study may require hundreds of experimental runs to explore a combination of multiple input factors. An average experiment resolution time of 45 minutes results in almost 250 hours of required manual labor to conduct our analysis. Fortunately, the built-in automation tool can process the manual labor needed by adjusting a user's specific input parameters, such as the Response Time, Negotiation Strategy, and flight trajectory plan, and these input parameters are automated throughout an entire negotiation process.

The automation system was built using a Python package called Selenium [16], which allows for the automation of several web-based interactions, providing the foundation to perform sensitivity analyses in a controlled environment. The goal of the automation system is to simulate the actions and decision-making that a real user would make in the negotiation tool. The types of interactions are simplified into physical interactions and decision-making actions. Physical interactions are described as the interaction of a user inputting information into the negotiation tool. These actions include hovering the mouse cursor over a clickable button, entering a numerical value inside an input box, choosing an item from a drop-down menu, evaluating the data from another user and responding to it, etc. The decision-making part of the automation relates to evaluating the generated data, including the amount of time left, the current required cost, and the response cost. With every decision that needs to be made, there must be some form of interaction on the web page. By modeling a system around this, we achieved a dynamic system that automates the negotiation tool's decision-making and physical interaction elements. Since the negotiation tool requires two users to work together to come to an agreement, each user can be simulated independently. The decisions and interactions of one simulated user will cause the other to evaluate the information received and make a decision correspondingly.

A full negotiation cycle can be automated by following a procedure shown in Fig. 8. Cooperation within the negotiation tool requires the participation of two users. The automation tool mimics cooperative human interaction by opening two side-by-side separate web browser pages connected to the web-based negotiation tool. Each experiment from the automation batch contains unique input variables for each operator that will change how each negotiation cycle plays out. When the first negotiation round begins, the left browser is always assumed to be the first proposer, which assumes the responsibility of proposing a trajectory to the responder. For the negotiation tool to generate a $f_{i,P}$, the negotiation tool will ask for an input proposal cost. Since the automation tool is not a human user, a consistent method must be determined to generate a value for the proposal cost. Our approach is to search for the required cost and create an internal proposal variable that takes the required cost rc and adds 1%. The added 1% to rc is necessary because one of the conditions for the program is that when a proposal cost is entered into the program, it must be greater than the required cost, which satisfies the monotonically increasing cost requirement. The challenge with this process is that the required cost is calculated in real-time on the web page rather than within the backend portion of the codebase. A solution to this challenge is to look within the HyperText Markup Language (HTML) code the web-based negotiation model runs on and find the unique HTML ID that identifies the required cost. This process is also used to identify any other necessary elements from the web page needed for automation, such as buttons, the time remaining, the response cost, etc. Once the required cost is obtained and 1% is added, this new value is automatically entered into the web interface as the proposal cost. It finds and clicks on the HTML buttons "Send cost" and "Send trajectory," which then switches the focus to the right browser. The right browser now becomes the responder. The automation tool clicks on "Generate Response Trajectory," which leads to the webpage that allows the responder to accept or decline the generated proposal and response trajectories. It evaluates the decision to accept or decline based on the response cost and the required cost values. If the response cost exceeds the required cost, the automation tool will click on the "Decline" button, which switches the roles of both browsers, and another negotiation round begins. If the response cost is less than the required cost, the automation tool will click the "Accept" button, and the overall negotiation ends. By automating the whole negotiation process, we were able to cut down on the time spent performing our sensitivity analysis, and we were able to cut out any potential human errors that could have occurred had we not automated this process.

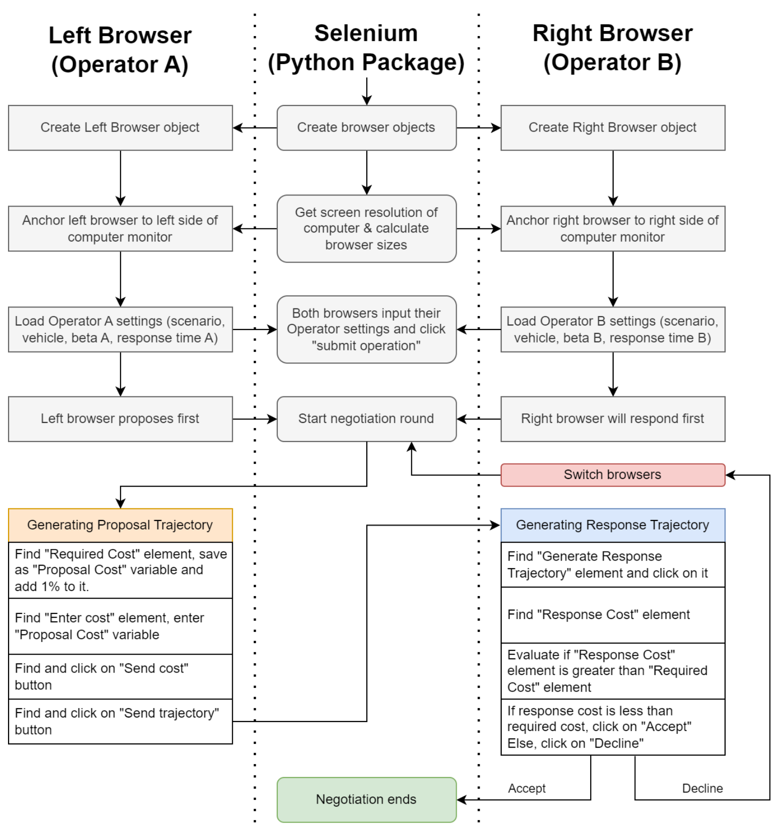

Fig. 8 Overview of the Automation algorithm used to simulate the experimental results.

VI. Applications of the Tool and Design of Experiment

This section will discuss the negotiation tool's applications and introduce the design of experiments to empirically demonstrate its capabilities. We will also outline the information we collected from each experiment, conduct a sensitivity analysis, and demonstrate the success of the developed tool in the next section.

A. Applications

This tool can be used in various scenarios specific to ETM conflict resolution. It is assumed that the operators using this tool are willing to share their flight trajectories to cooperate and that sufficient time is given to negotiate. The purpose of this tool is not for last-minute deconfliction, but to provide an efficient and equitable way to solve conflict between two operators with sufficient time for negotiation. The tool can simulate and evaluate a wide variety of inputs and outputs, thereby potentially uncovering interesting relationships between different input factors and the output metrics that could lead to complicated or delayed negotiation under specific input conditions. Running a batch simulation through a controlled automation setting allows us to set up multiple run conditions with different input factors. Detailed information about these input factors, including how they relate to ETM scenarios, is explained next.

B. Factorial Design and Input Variables

We chose to test each operator's input variables to observe the effect of their interactions ensuring that the negotiation would be successful in many different scenarios. Table 1 summarizes the factors and levels chosen for experimentation. The following subsections will explain each factor we are testing in more depth.

Table 1 Table of Factors, levels, and abbreviations that have been included in testing.

Factors	Abr.	**Levels**
Crossing Angles	C	Crossing
	SC	Shallow Crossing
	H	Head on
Aircraft Type	G	Global Hawk RQ-4
	S	Sunglider HAPS UAV
Response Time	I	Instant
	L	Long
Negotiation Strategy	B	Boulware
	L	Linear
	C	Conceder

1. Crossing Angles

The Crossing Angles between two aircraft trajectories can categorize different conflict scenarios. Suppose one ETM vehicle is flying in a straight path and another aircraft has a trajectory that crosses the first operator's trajectory at some point in the future. We can measure the angle between these two trajectories. Based on the range the angle falls into, the type of conflict can be categorized. Refer to Fig. 9 to visualize the angle ranges between two trajectories that cross paths. If the angle between the two aircraft is acute, between 0° to 45°, the case can be classified as a Shallow Crossing conflict. The conflict can be categorized as a Crossing if the angle between the two trajectories is between 45° to 135°. If the angle between the two trajectories is obtuse, between 135° to 180°, the case can be classified as a Head On conflict. Refer to Table 2 for a quick summary.

Table 2 Summary of conflict scenarios categorized by crossing angles.

Category	Angle Range
Shallow Crossing	0° – 45°
Crossing	45° – 135°
Head On	135° – 180°

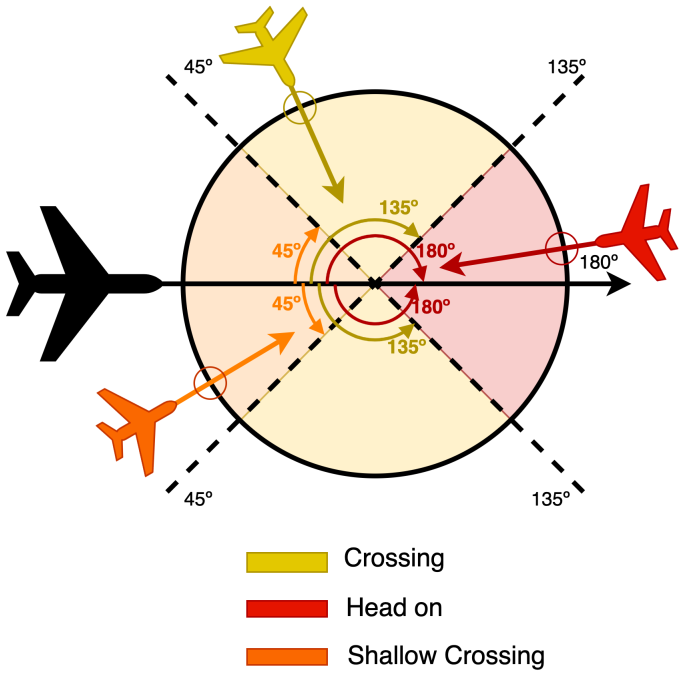

Fig. 9 Visualization of crossing angles categorized by types of conflict.

2. Aircraft Type

The vehicles used in these experiments are meant to be as close as possible to those in the real world. To test how the tool can handle aircraft of various speeds and maneuverability in reality, the aircraft and trajectories are modeled after real vehicles that can operate in Upper Class E airspace. The two unique vehicles chosen for testing are the Global Hawk RQ-4 [17], and Sunglider solar-powered high-altitude pseudo-satellite (HAPS) unmanned aerial vehicle (UAV) [18]. The maximum bank angle (μ) used for the Global Hawk RQ-4 is reported to be 14.8% based on performance analysis and flight testing [19]. The speed for the global hawk reported by the US Air Force [17] is 310 knots. The Sunglider HAPS has been found to have an average cruise speed of 68 mph [18]. The summary of these parameters for the vehicles can be seen in Table 3. The parameters for these two types of vehicles have been converted into the same unit, and their maximum turn rate has been found with Eq. (3).

$$\text{turn rate} = \frac{\tan(\frac{\mu \times \pi}{180}) \times \pi}{180 \times \text{velocity}} \tag{3}$$

Table 3 Summary of studied vehicle parameters.

Aircraft	Max Bank Angle	Average Cruise Speed	Meters per Second	Max Turn Rate
Global Hawk	14.8%	357 MPH	159.59	0.93
Sunglider	5%	68 MPH	30.40	1.62

3. Response Time

Response time pertains to the time it takes an operator to complete their response for any specific step in negotiation. In previous studies [3], it was found that increased Response Times can disadvantage the slower operator in negotiation. We are interested in extending the hypothesis of the previous results by adding in more input variables and testing whether or not that claim holds true. The summary for the Response Time parameters can be found in Table 4.

Table 4 Summary of response times by duration.

Category	Response Time
Instant	1 second
Long	600 seconds

4. Negotiation Strategy

Similar to Response Times, we are also interested in extending the previous studies' hypothesis to see whether different Negotiation Strategies have a meaningful impact on the final output measures. The Negotiation Strategy β values for the Boulware (β » 1), Linear (β = 1), and Conceder (β « 1) strategies were chosen to be distinguishingly different from each other, which might result in unique normalized flight distance behaviors among the three strategies. The summary of the Negotiation Strategies used within our experiments can be found in Table 5.

Table 5 Summary of Negotiation Strategies by category.

Category	Strategy Type
Boulware	$\beta = 4$
Linear	$\beta = 1$
Conceder	$\beta = \frac{1}{4}$

C. Output Measures

The following section briefly describes the output metrics measured at the end of a negotiation. These output metrics will be used to conduct a sensitivity analysis with the input variables to determine how different input combinations can affect the outcome of a negotiation.

1. Number of Rounds

The Number of Rounds refers to the number of full negotiation cycles, which consists of the flight trajectories from a proposing operator and a responding operator.

2. Total Time

Total Time refers to the time it takes for a negotiation to finish from the start to the end of a negotiation.

3. Ratio of the Extra Flight Distance

The Ratio of the Extra Flight Distance measures the Extra Flight Distance sum divided by the Baseline Extra Flight Distance for operators A or B, which is the extra distance that would have been incurred if operator A or B had taken on 100% of the responsibility for resolving the conflict.

VII. Experiment Results

We are interested in finding correlations between the experimental input variables and the output measures. A total of 324 experiments were run using the combinatorics as laid out in Table 1. The results of these experiments show the final output of a two-party negotiation and how each parameter can affect the overall negotiation process. To demonstrate how the experimental parameters are set up, Table 6 shows the first ten out of 324 experiments that were run. The values shown in the table are the control variables that differentiate each experiment.

Table 6 Table depicting the input variable set up for the first ten experiments.

Experiment	Crossing Angle	Vehicle Pair	Response Time A	Response Time B	β_A	β_B
1	C	G-G	1s	1s	1	1
2	C	G-G	1s	1s	1	4
3	C	G-G	1s	1s	1	0.25
4	C	G-G	1s	1s	4	1
5	C	G-G	1s	1s	4	4
6	C	G-G	1s	1s	4	0.25
7	C	G-G	1s	1s	0.25	1
8	C	G-G	1s	1s	0.25	4
9	C	G-G	1s	1s	0.25	0.25
10	C	G-G	1s	600s	1	1

To observe the impact of each parameter on the outcome of the experiments, a sensitivity analysis was carried out with a change in the input variables, which include the Crossing Angle, Aircraft Types, Response Times, and Negotiation Strategy, versus the output measures, which include the Number of Rounds, Total Time, and Ratio of the Extra Flight Distances over Extra Baseline Flight Distances. A statistical analysis was conducted across all combinations using a non-parametric Kruskal-Wallis H test to analyze the significance of the relationship between our input variables and output factors. The results of this statistical analysis results will help us identify the possible factors that could affect negotiation.

A. Number of Rounds

Total number of negotiation rounds was recorded for each simulation run to determine how different conditions would impact the amount of negotiation that would occur. Statistical tests were conducted to evaluate the impact of the input variables on the Number of Rounds, and the results that are significant are reported below.

The Number of Rounds were averaged across different Crossing Angles and Aircraft Types. Figure 10 shows the results for the Crossing Angles. The Number of Rounds were fewest for Head On scenarios, followed by regular Crossing angle scenarios and Shallow crossing scenarios, in that sequence. The results suggest that perhaps the closure rate of a conflict impacts the time pressure to complete the negotiations. Figure 11 shows the results for the Aircraft Type. The Number of Rounds were similar for the Global Hawk pairs and Global Hawk-Sunglider combination, compared to Sunglider pairs that required nearly twice as many rounds. These results suggest that aircraft speed may also impact the Number of Rounds, possibly because slower aircraft can also impact the closure rate.

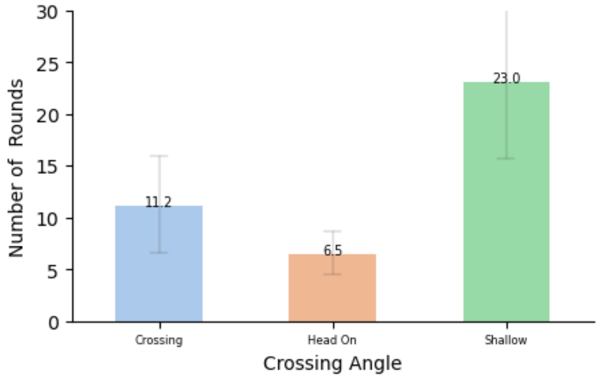

Fig. 10 Number of Rounds vs. Crossing Angle.

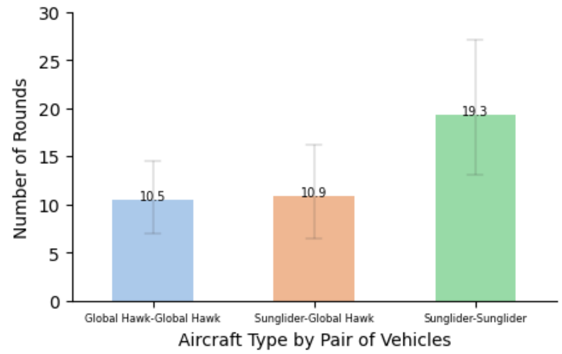

Fig. 11 Number of Rounds vs. Aircraft Type.

Figure 12 shows the number of negotiation rounds for each of the Response Time pairs. The results showed a large number of negotiation rounds when both vehicle operators responded within 1 second of receiving the other operator's proposal. The results for 1sec-1sec response time were expected since shorter Response Times mean that operators can complete each round more quickly and have more overall time to negotiate with one another. As shown in Fig. 12 , there is a significant reduction in the average Number of Rounds if any of the vehicles have a Response Time of 600 seconds instead of 1 second, which is interesting in that only a few rounds are completed even when one operator responds quickly while the other operator responds slowly. This suggests that multiple rounds of negotiations are only feasible when both vehicles can respond in rapid succession.

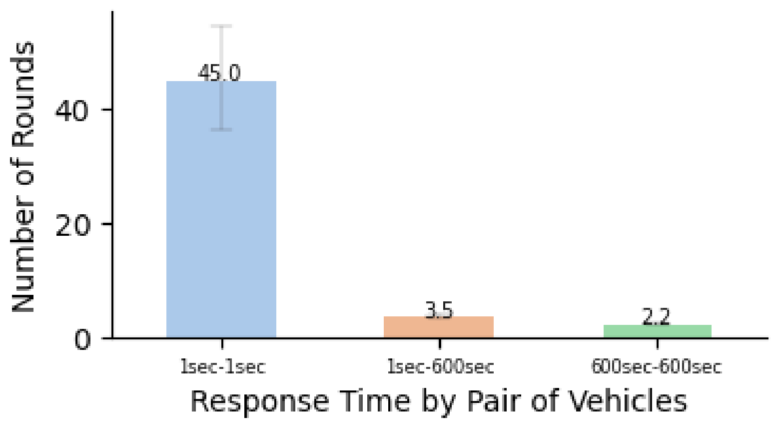

Fig. 12 The Number of Rounds vs. Response Time.

Figure 13 shows the number of negotiation rounds for different negotiation strategies by pairs of vehicles. The overall results showed consistent patterns, where the Number of Rounds were fewest when both vehicle operators used Conceder strategies and greatest when they both used Boulware strategies. When the strategies were mixed, the Number of Rounds seemed to vary, with a general pattern that Conceder strategy resulting in fewer rounds, Boulware strategy resulting in more, and Linear strategy somewhere in-between. These results suggest that when one or more vehicle operator "concedes" and resolve more of the conflict earlier in the negotiation time frame, the negotiation tends to complete with fewer rounds, while Boulware strategy has an opposite effect of extending the negotiation rounds by offering to resolve the less of the conflicts early in the negotiation time frame.

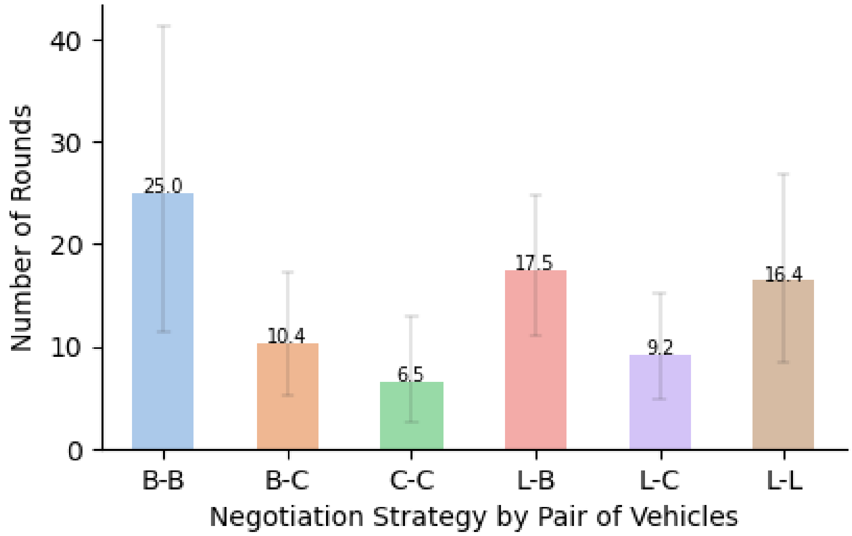

Fig. 13 The Number of Rounds vs. Response Time.

B. Total Time

The total negotiation completion time was calculated and examined across different conditions. The analysis suggested that all of the input variables had an impact on the length of the Total Time. Figure 14 shows the median Total Time for the different Crossing Angle types. Although the Total Time for the Head On angles were somewhat expected to have the shortest time due to the fastest closure rate, the results showed that The Total Time was the shortest for the regular Crossing angles, followed by the Head On angles, and then the Shallow angles. Figure 15 shows the median Total Time for the different Aircraft Types. Different Aircraft Types significantly affect the Total Time, as the Global Hawk, which is a more maneuverable aircraft than the Sunglider, had nearly half the Total Time as the Sunglider pairs, which had the longest Total Time (see Fig. 15).

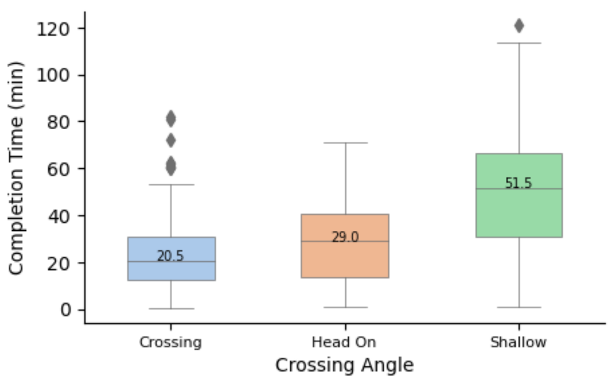

Fig. 14 The Total Time vs. Crossing Angle

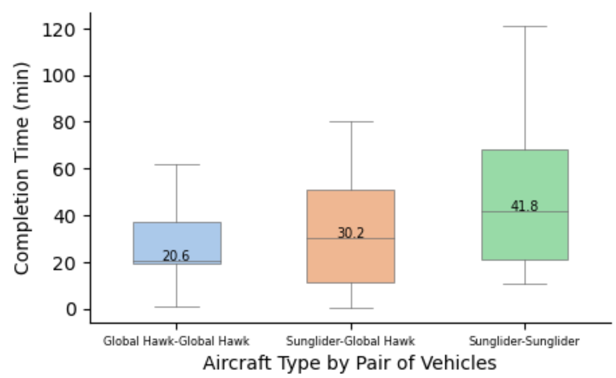

Fig. 15 The Total Time vs. Aircraft Type.

Figure 16 shows the total negotiation completion time for each of the Response Time pairs. The Total Time was the shortest when both operators had a 1-second Response Time, and the median Total Time was the longest when both operators had a 600-second Response Time. This suggests that operators can reach a quicker mutual agreement if the Response Time is shorter.

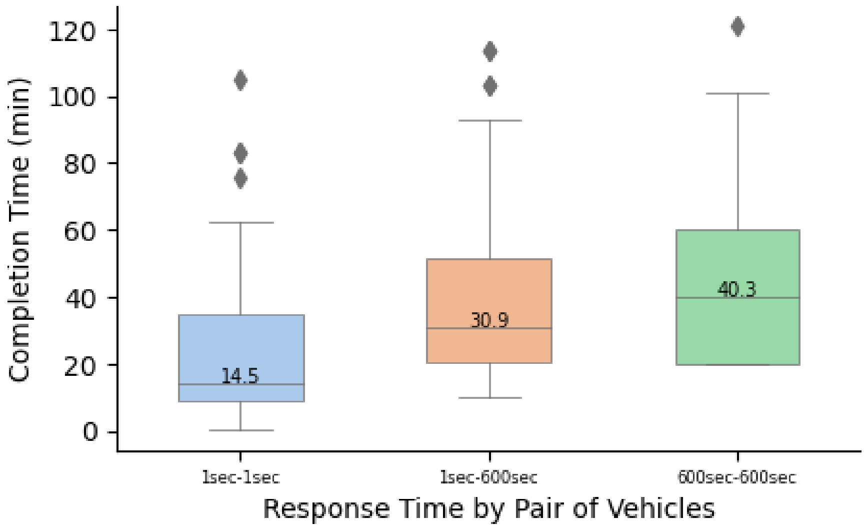

Fig. 16 The Total Time vs. Response Time.

The significance of the impact of Negotiation Strategy on Total Time can be observed in Fig. 17. The results align with our expectations of how the Negotiation Strategy should affect the negotiation. The Boulware-Boulware pair has the largest median value for Total Time, which makes sense since the operator with the Boulware strategy is more hesitant to maneuver until the negotiation time window is low. Similarly, the Conceder-Conceder pair has the smallest median value for Total Time, likely due to operators maneuvering more aggressively early in the negotiation time window. Interestingly, any conditions in which one of the two operators employs the Conceder strategy also resulted in a shorter Total Time, suggesting that early concession by any of the operators may result in a quick resolution to the negotiation.

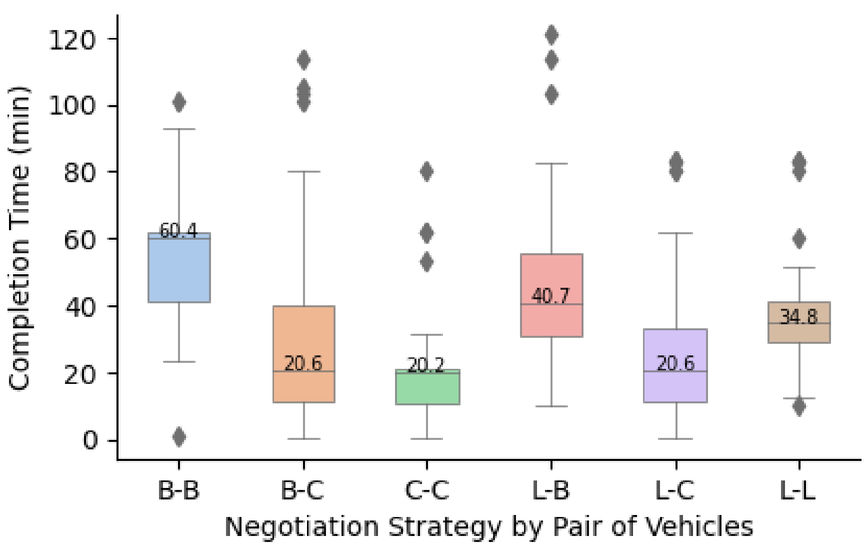

Fig. 17 The Total Time vs. Negotiation Strategy.

C. Ratio of the Extra Flight Distance Sum over Extra Baseline Flight Distance by A or B

In an ideal negotiation, two cooperative operators would both contribute a fair share of maneuver responsibility out of 100% to resolve conflict. In such an outcome, it would be desirable if the negotiated flight paths were also more efficient, resulting in less total extra distance flown than those without such negotiation. A direct measurement to assess the efficiency is to examine the sum of the extra flight distances flown by both vehicles in the negotiated solution, divided by the extra distance flown by each vehicle's corresponding baseline trajectory without the negotiation. This measurement will return a ratio score that describes both operators' added cooperative maneuver responsibility compared to if either operator took full maneuver responsibility. The data shown in Fig. 18 suggests that the total extra flight distance incurred by negotiation is generally far less than the extra distances incurred without negotiation for either operator A or B. This benefits both operators since there is a high likelihood that the extra distance sum required will be less than that with either participant's full responsibility. It can be claimed that on an individual basis, each operator can reduce their total extra flight distance by an average of 24% to 27%, since the median ratio score for operators A and B reside around the 75% average. A deeper analysis of the results suggests that on an individual basis, an operator may be able to save an average of 65% of their extra flight distance. Therefore, the implications of the results demonstrate that operators stand to benefit themselves and each other by participating in cooperative negotiation.

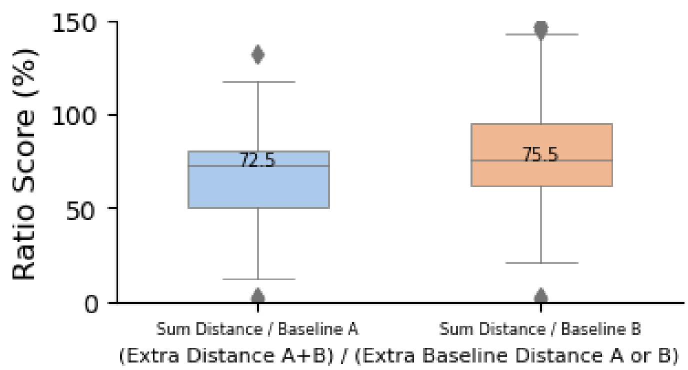

Fig. 18 The Ratio of Extra Distance Sum over Baseline A or B.

A potential loss in Sum Ratio efficiency is noted when comparing the Sum Ratio with different Response Times. From observations in Fig. 19, it can be seen that the 1sec-1sec Response Time pair (denoted by I-I for "instant-instant") has the lowest median range while the 600sec-600sec Response Time pair (denoted by L-L for "long-long") has the highest median range. There is an observable increase in median scores as the Response Time pairs increase, and the Ratio Scores have a higher likelihood of going past the 100% threshold when the Response Times are longer. The general observation can support that faster Response Times will result in a more efficient Sum Ratio result.

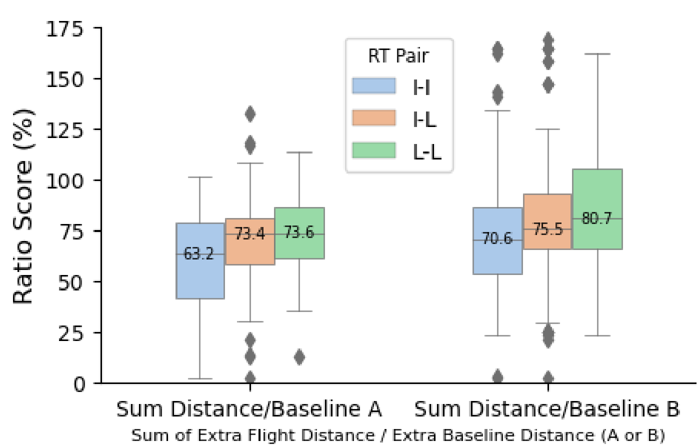

Fig. 19 The Sum Ratio vs Response Time.

To add visual context to operators' shared maneuver responsibility to resolve conflict, Figs. 20 and 21 showcase conflict resolution from a 90-Degree crossing Global-Hawk/Global-Hawk vehicle pair. In the left map, Fig. 20 displays the mutually resolved conflict between both operators after negotiation. The right map, Fig. 21, displays the routes if either operator takes full maneuver responsibility. In the shown experiment, the Sum Ratio values for operators A (blue) and B (red) are 37.93% and 52.29%, which indicates that the extra flight distance sum of the trajectories with resolved conflict is about half the distance of either baseline trajectory, as shown in Fig. 21.

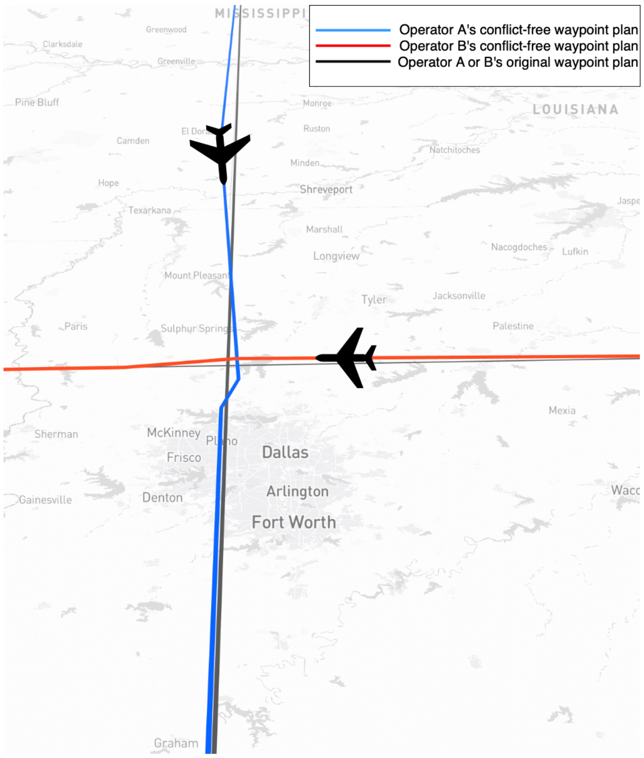

Fig. 20 The mutually agreed upon resolved conflict after negotiation between two operators.

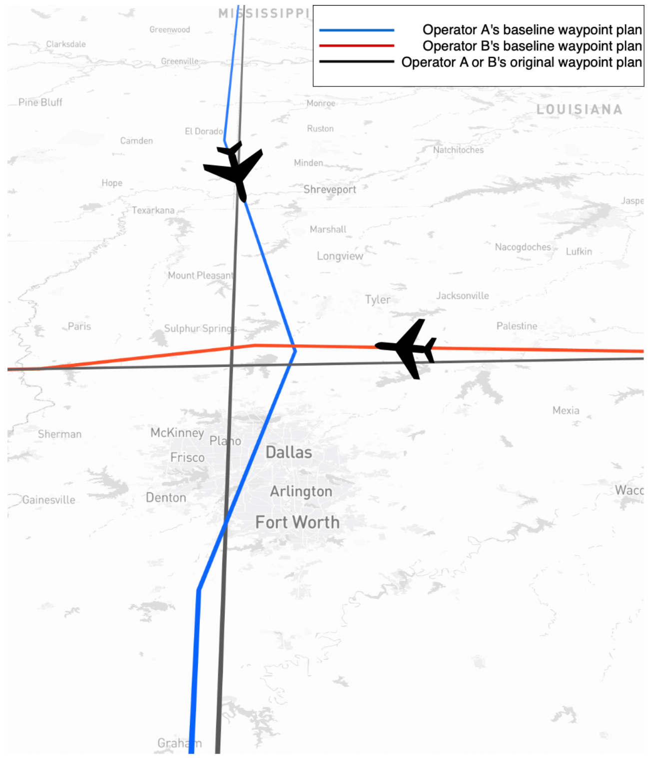

Fig. 21 The Baseline Trajectories if either operator took full maneuver responsibility.

The ratio of extra flight distance due to negotiation vs. baseline flight distance was expected to be impacted by the Negotiation Strategy. Although the results showed a slightly lower sum distance for the Boulware-Boulware pair strategy (M = 67.4% and 68.3% for Baseline A and B, respectively), compared to other strategies (ranging between 69.7% to 77.6%), the results were not statistically significant. For the Crossing Angles and Aircraft Types, the results showed differing trends when compared against the Extra Flight Distance for Baseline A vs. Baseline B. Therefore, further analyses are needed before drawing any definitive conclusions.

VIII. Key Observations

The results of the study provided multiple insights into how the Negotiation Strategies and operator Response Times affect the efficiency of the final negotiated flight trajectories and whether the negotiation paradigm provided benefits to each operator. Furthermore, additional input variables on the Crossing Angles and the vehicle types were examined for the potential sensitivity of the results based on these parameters. Overall, the following are the key observations that were gathered from the study:

- Most output variables were affected by the Response Times or the Negotiation Strategy value, as well as the Crossing Angles and Aircraft Types.
- All experiments ended with a successful, mutually agreed-upon conflict resolution, demonstrating the tool's effectiveness in solving conflict with various input variables. The sensitivity analysis also suggests that participants will likely resolve conflict with a collaborative contribution sum of around 75% of the non-negotiation conflict resolution.

- Shorter Response Times are beneficial to all negotiating participants. It enables more rounds to process within the negotiation, directly correlating to a higher likelihood of a decreased contribution sum needed to resolve conflict. In this context, the greater number of negotiation rounds was considered to be beneficial, but there also may be a potential for creating an excessive workload due to faster cycles of negotiation. Overall, shorter Response Times are beneficial for cooperative participants since it directly correlates to less overall flight distances and/or time required to resolve conflict. Longer Response Times are problematic, leading to less efficient negotiations, with increased final contribution sums, longer completion times, and fewer Number of Rounds.
- There are two notable behaviors with varying Negotiation Strategy values. Conceder strategies with a $\beta << 1$ are more likely to reduce the total time spent on negotiation, as well as the number of negotiation rounds needed to come to a resolution. This makes sense since an earlier concession that offers a greater portion of the resolutions should allow quicker resolution with fewer negotiation rounds. Boulware strategies with a $\beta >> 1$ have the longest Total Times and a greater number of negotiation rounds prior to reaching a resolution, but they may potentially resolve conflict with shorter flight distances, although the results were not statistically significant. The Negotiation Strategies affected the output measures in a more complex and interesting manner, and further investigation is needed to better understand the depth and impact of Negotiation Strategies.
- The output variables were impacted by Aircraft Types and Crossing Angles with similar trends. Factors that could potentially lengthen the time to conflict or decrease closure rates, such as slow vehicle pairs (e.g. Sunglider-Sunglider pair) or shallow crossing angles, generally increased the Total Time and Number of Rounds to reach the completion of the negotiation. Faster vehicle pairs (e.g. Global Hawk-Global Hawk pair) and closure rates (e.g. Head On crossings) generally resulted in shorter completion time and fewer negotiation rounds, with the caveat that the regular Crossing Angles produced shorter Total Time than Head On crossings. Further research is needed to fully understand the complex interactions of vehicles and Crossing Angles.

IX. Summary and Future Work

A. Summary

This paper introduces the first interactive web-based program to facilitate negotiation, detect conflict, and generate alternative flight trajectory plans for operators in real-time. For facilitated negotiation to be successful, a platform that can handle different configurations in a flexible manner is needed. We developed a web application that can take an operator's desire to maneuver as a measurement of a private cost and streamline the complexities of resolving conflict with our internal algorithms. We were able to stress-test our tool through an automation system that allowed us to set up several controlled experiments with different input parameters. We observed the effectiveness of our program by measuring key metrics such as the Number of Rounds, the Total Time, and the Ratio of Extra Flight Distances over Extra Baseline Flight Distances. Not only was our tool able to successfully resolve conflict with all 324 experiments, but also we observed the statistical significance of the impact of our input variables on our output measures. This gives us a better understanding of how certain relationships between our input variables and output measures can affect the overall efficiencies of the final outcomes. The results of our sensitivity analysis demonstrate the effectiveness of our negotiation model in a real-time setting.

B. Future Work

Our program is still a work in progress, as many features and improvements can be implemented. For example, a real-time mapping system so operators can see where their vehicles are during negotiation. Our graph system uses a static pre-rendered image, which cannot be zoomed in or modified. This program only generates new flight trajectory plans that maneuver to the left or right relative to the operator. As a result, there are potential undiscovered solutions that may lead to more optimized final outcomes. As described in referenced papers [11], other methods include climbing, descending, slowing down, speeding up, or a combination of these methods, which will be implemented in future program versions. The experiments were also done with a mean value wind sum of 0 knots, but further iterations of the program will consider non-zero wind speeds. More experiments and sensitivity analysis will be carried out to better understand the relationship between the input variables and output factors, and their impact on the negotiation process and outcomes. One of the main goals for the future of this program is to support multi-party negotiations. With an increase in traffic in Upper-Class E airspace, there will be scenarios that involve more than two operators. Current research is in progress to extend the current negotiation model used in this program to a multi-party model.

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