CELLULAR AUTOMATA MODELING OF EN ROUTE AND ARRIVAL SELF-SPACING FOR AUTONOMOUS AIRCRAFTS

Charles Kim

ckim@howard.edu

Department of Electrical and Computer Engineering

Howard University.

ATCA Conference 2005

HIGHLIGHTS OF THE PAPER

- Aircraft Navigation
- What is Cellular Automaton?
- Conway Game of Life as a pioneer work in cellular automaton concept.
- Directional cellular automata as applied to aircraft navigation.
- Display of Simulation results performed in Matlab Platform.
- Advantages of this concept over voice communication in the air-traffic system.

Air Traffic Control and Navigation Operational Features

- The current practice has the various sectional controllers maintaining voice communications with the pilots to ensure safe navigation.

- This approach places a lot of communication burden on the controllers as well as the pilots.

- Air traffic control via voice communication places its success on timely and accurate human judgment.

- The system is prone to errors as there is no clear cut mathematical relation to model human actions.

- Navigational aids like the one presented in this paper stand to augment the operational features of the present approach.

MOTIVATION FOR THIS RESEARCH

- There is a gradual shift from a radar based system to a space based system for the air traffic control and navigation.

- In this new approach, each autonomous aircraft equipped with on-board transponder and GPS system would be aware of its position and those of other aircrafts in its navigation space.

- The navigation, especially in the en-route domain and near a terminal space can be done by automated self space approach.

- The directional cellular automata algorithm proposed in this paper can be used to model and simulate in 2D plane a coordinated and reliable pattern of navigation in the en-route domain for the autonomous aircrafts.

What is Cellular Automaton(CA)?

- CA is a dynamical system which consists of a regular grid of cells, each of which can assume a finite number of possible states, and updated synchronously in discrete time steps, according to a local, identical interaction rule.

- The state of a cell at a given discrete time, t^i is determined by the previous states of a surrounding neighborhood of cells at time, t^{i-1}.

- The application of cellular automata in physical simulations can provide some interesting results that will help track the trajectories of system dynamics.

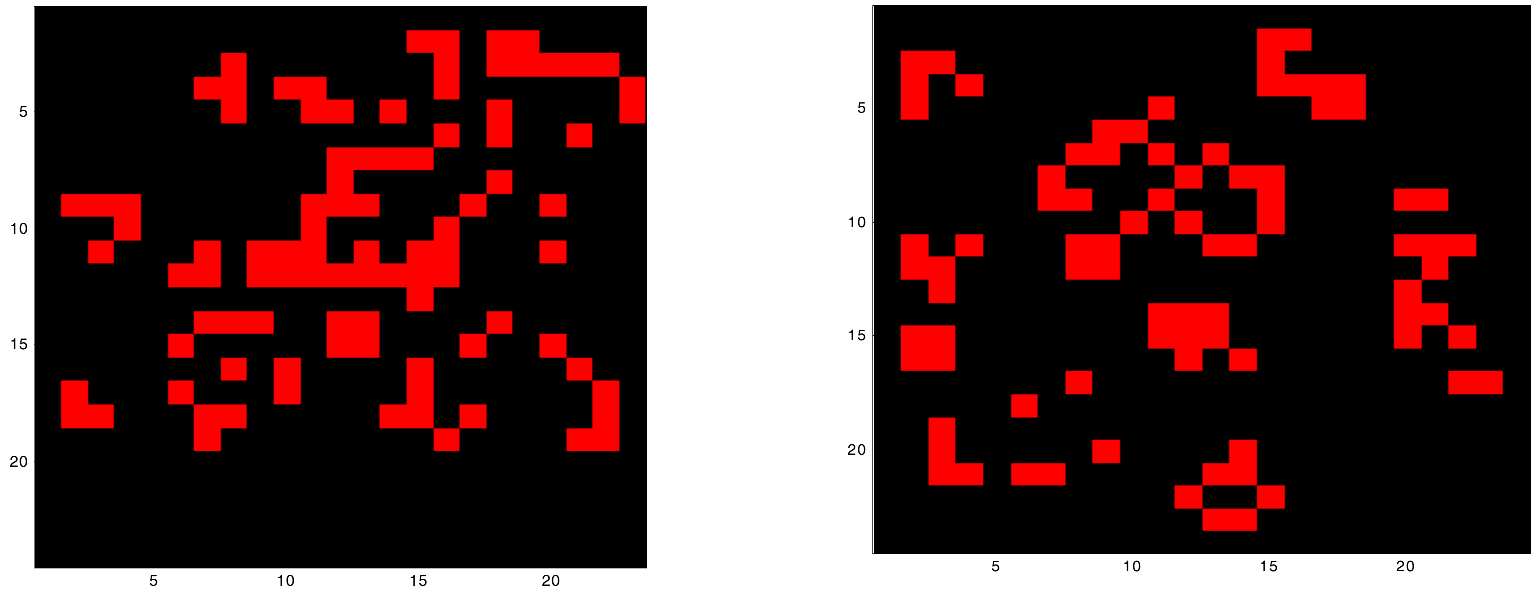
- In a CA system, each cell takes either state “1” or state “0” and evolves in discrete time and space according to a uniform local rule.

- The cell with “1” state indicates it is occupied by an object and the one with “0” is empty and ready to be occupied.

- The conventional cellular automata used to generate patterns and which is widely applied in several fields of physical sciences evolve randomly to create complex or simple patterns.

- Converse to the random generation of patterns in the traditional CA, the directional cellular automata navigates the objects in a directional pattern.

- Aircrafts, being the dynamic objects here can navigate in a self spaced sense from departure point to destination point safely.



Random patterns generated by traditional CA local rule in 2 time steps

- The patterns displayed above were randomly generated in two successive time steps.

- The red patches represent cells that are occupied while the dark spots are empty cells.

- A cell that is occupied in a given time step may be empty or continue be occupied in the next time step.

Cellular Automaton and Game of Life

- The “Game of Life” invented by John Conway in 1970 is just one example of a traditional cellular automaton which find a wide range of applications in biological sciences.

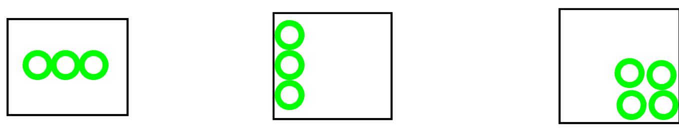
- Life is played on a grid of square cells, and once the “pieces” are placed in the starting position, the rule determines everything that happens later.

- Each cell in the grid has a neighborhood consisting of the eight cells in every direction including diagonals.

- The shapes assumed by the pieces in the subsequent time steps are randomly generated.

•A dead cell with exactly three live neighbors becomes a live cell (birth)

•A live cell with two or three live neighbors stays alive (survival)



•Aside from the above two circumstances, a cell dies or remains dead

Fig.2   A 2-D pictorial representation of “Game of Life” cellular automaton

<u>Transition Function for the local automation is as follows:</u>

- There are two states: **alive, not alive**.
- If 2 or 3 neighbors of a cell are **alive** and it is currently **alive**, its next state is **alive**
- If 3 neighbors of a cell are **alive** and its is currently **not alive**, its next state is **alive**
- Otherwise the next state is **not alive**

Modeling of Directional Cellular Automata(CA)

- The National Air Space System(NAS) is modeled as a 2D M-by-N homogeneous array of square "cells".

- Each cell takes on either state **"1"** or state **"0",** and evolves in discrete time and space according to a uniform local rule. A cell in state "1" is occupied, while a cell in state "0"is empty and ready to be occupied.

- The position of an aircraft, severe weather area, restricted fly zones are all defined in the cell state space as **"1".**

- An aircraft occupying a defined "cell position" in a given discrete time step interacts with the neighborhood sites and by a simple directional interactive CA algorithm advances one step to the next cell that optimizes its path to the destination point.

DIRECTIONAL CA ALGORITHM AND AUTONOMOUS FLIGHT NAVIGATION

- **Aircrafts equipped with GPS and transponders are best suited for the application of CA algorithm.**

- **Aircrafts being aware of their positions and those of other aircrafts in the airspace allows for the collection of real time data.**

- **The CA algorithm processes information collected from the approaching aircrafts that are posed with conflict situations and provides the pilot with the optimal flight advisory maneuvering for separation assurance.**

- **This automated self spacing approach ensures that the optimal path of the respective flights to their destination points are maintained, while avoiding conflicts.**

- **The directional CA algorithm also processes information on areas of severe weather conditions and safe-fly zones, and provides the pilot with the best maneuvering option.**

DIRECTIONAL CA ALGORITHM LOCAL INTERACTION RULE

Define the spatial coordinates of the aircraft departure and destination points in a 2D M-by-N size array as:

X_i : x coordinate of the departure cell,

X_f : x coordinate of the destination cell,

Where, X_i, X_f = 1, 2, 3 …N

Y_i : y coordinate of the departure cell

Y_f : y coordinate of the destination cell.

Where, Y_i, Y_f = 1, 2, 3 …M

A simple directional CA rule written in terms of the variables defined above is:

CA Rule:

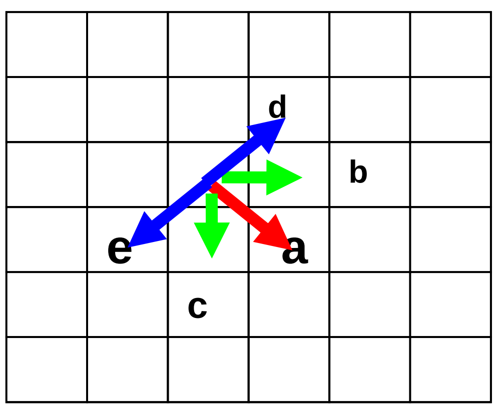
If $((X_f - X_i) > 0)$,	**Move right (or East).**
If $((Y_f - Y_i) > 0)$,	**Move down (or South).**
If $((X_f - X_i) < 0)$,	**Move left (or West).**
If $((Y_f - Y_i) < 0)$,	**Move up (or North).**
If $((X_f - X_i) = 0)$,	**No horizontal move.**
If $((Y_f - Y_i) = 0)$,	**No Vertical move**.

These base rules are combined using Boolean combinatorial logic to direct the navigation of an aircraft in discrete time and space by recommending the next cell along the optimal path.

THE MECHANICS OF THE DIRECTIONAL CA ALGORITHM

- **The CA search algorithm functions to achieve two major objectives namely:**
  - **Navigate an aircraft through an optimal path in no conflict scenario to maintain pre-planned flight route.**
  - **Maneuver appropriately when faced with conflict to resolve it and as well maintain the best optimal path.**

- **The algorithm guided by the spatial coordinates of an aircraft's departure and destination points respectively, coupled with the status of the cells in the neighborhood of the aircraft gives the best maneuvering advisory option.**



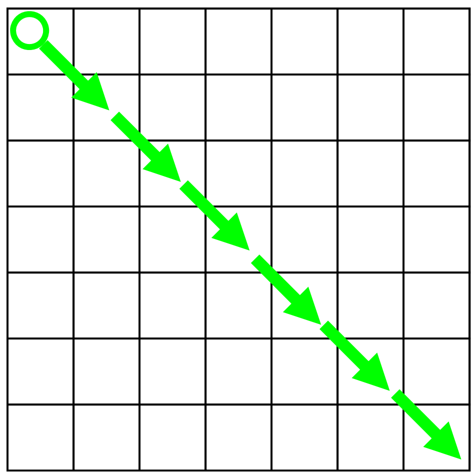
Prioritized Directional Navigation

a → 1st Priority

b or c → 2nd Priority

d or e → 3rd Priority

Fig. 3. Hierarchical Search in CA model



If $((X_f - X_i) > 0)$, Move right (or East).

If $((Y_f - Y_i) > 0)$, Move down (or South).

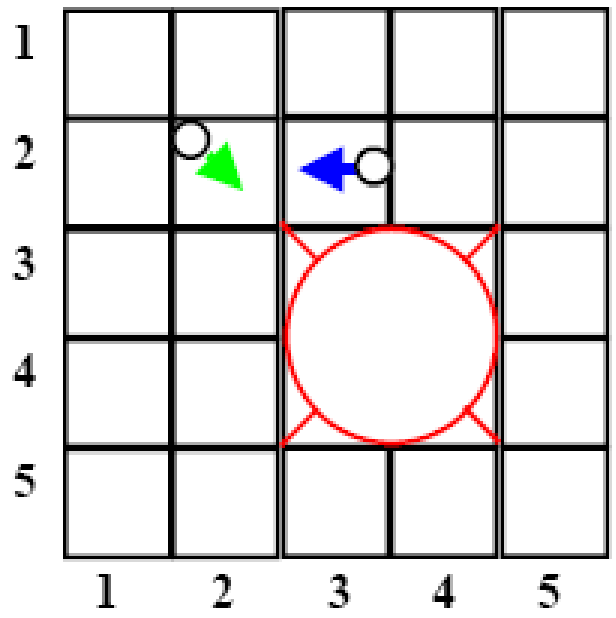
Movement here is from top left corner to the right bottom corner.

A South East bound Flight along the Optimal Path in No Conflict situation.

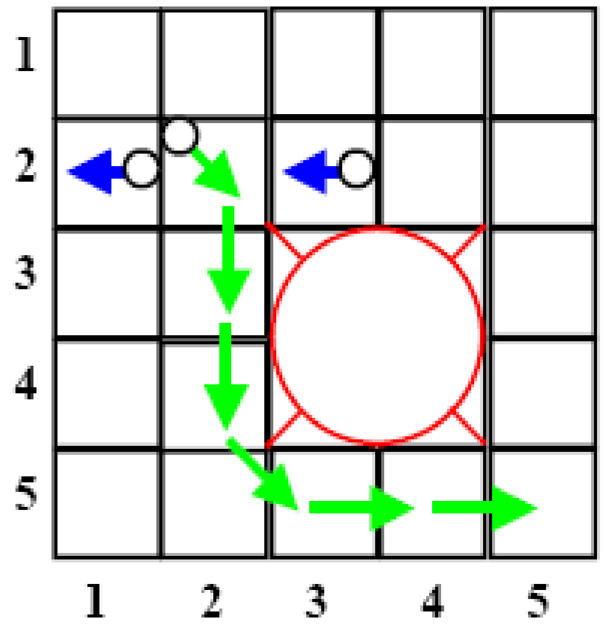
- The Figure above depicts a southeast bound flight along the optimal path.

- The CA algorithm selects both the “Down” and “Right” moves to direct the flight assumed to depart from the cell in the top left position to a destination cell in the bottom right position.

- Navigation along the diagonal path receives the highest priority in this case.



Flight faced with Conflict.



Flight Path after Conflict resolution.

- Figure 5a shows two aircrafts faced with the danger of collision, and as well restricted from using the air space marked in red.

- The directional CA rule resolves this conflict in figure 5b by redirecting the headings of the aircrafts in the best possible paths, which optimizes navigation to their respective destination points while avoiding collision.

DISPLAY OF SIMULATION RESULTS FOR DIFFERENT SCENARIOS

Scenario 1-Single Flight Maneuvering Through Randomly Placed Restricted Zones

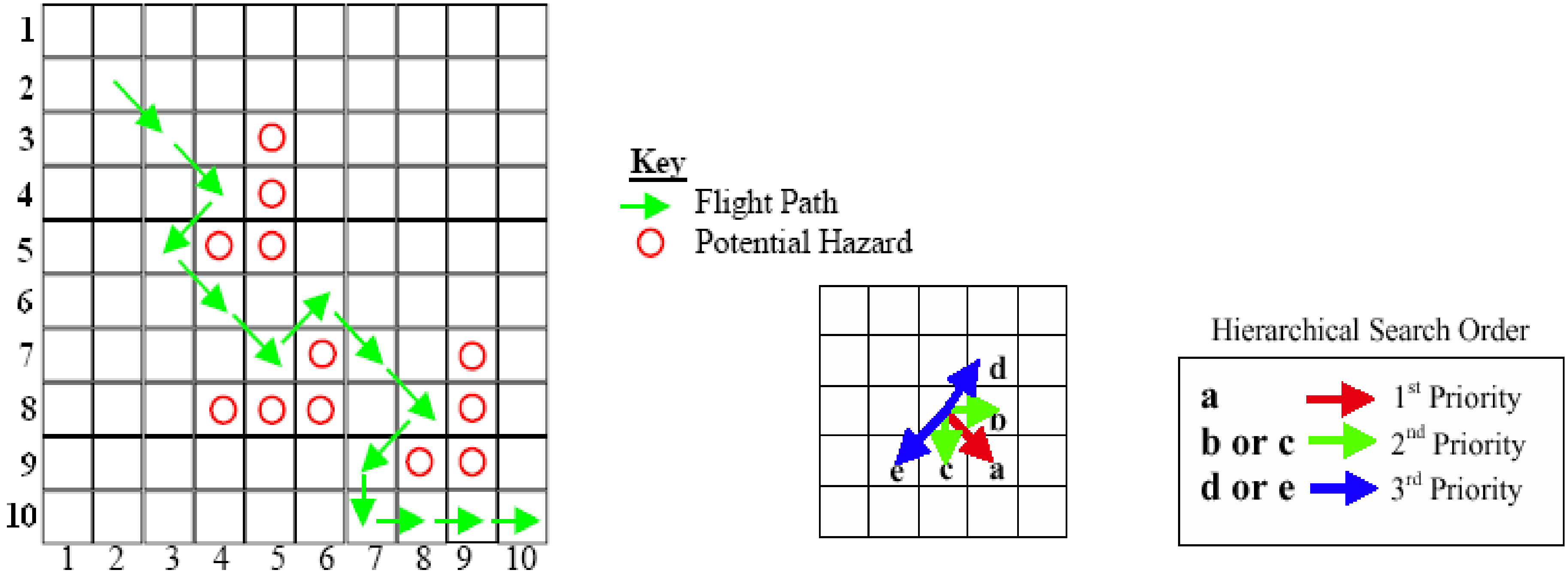


Fig.7 Simulated Trajectory Paths of Flight in Conflict Resolution

- **Navigation here is from departure point CELL(2,2) to CELL (10,10) in the southeast direction.**

- **Obstructions which represent bad weather areas and restricted fly zones are strategically placed along the flights path as shown in figure 7.**

- **Prioritized navigation to maintain optimal path trajectory is performed successively in discrete time steps to enable the aircraft maneuver properly.**

Scenario 2- Four Autonomous Aircrafts Heading For Different Directions.

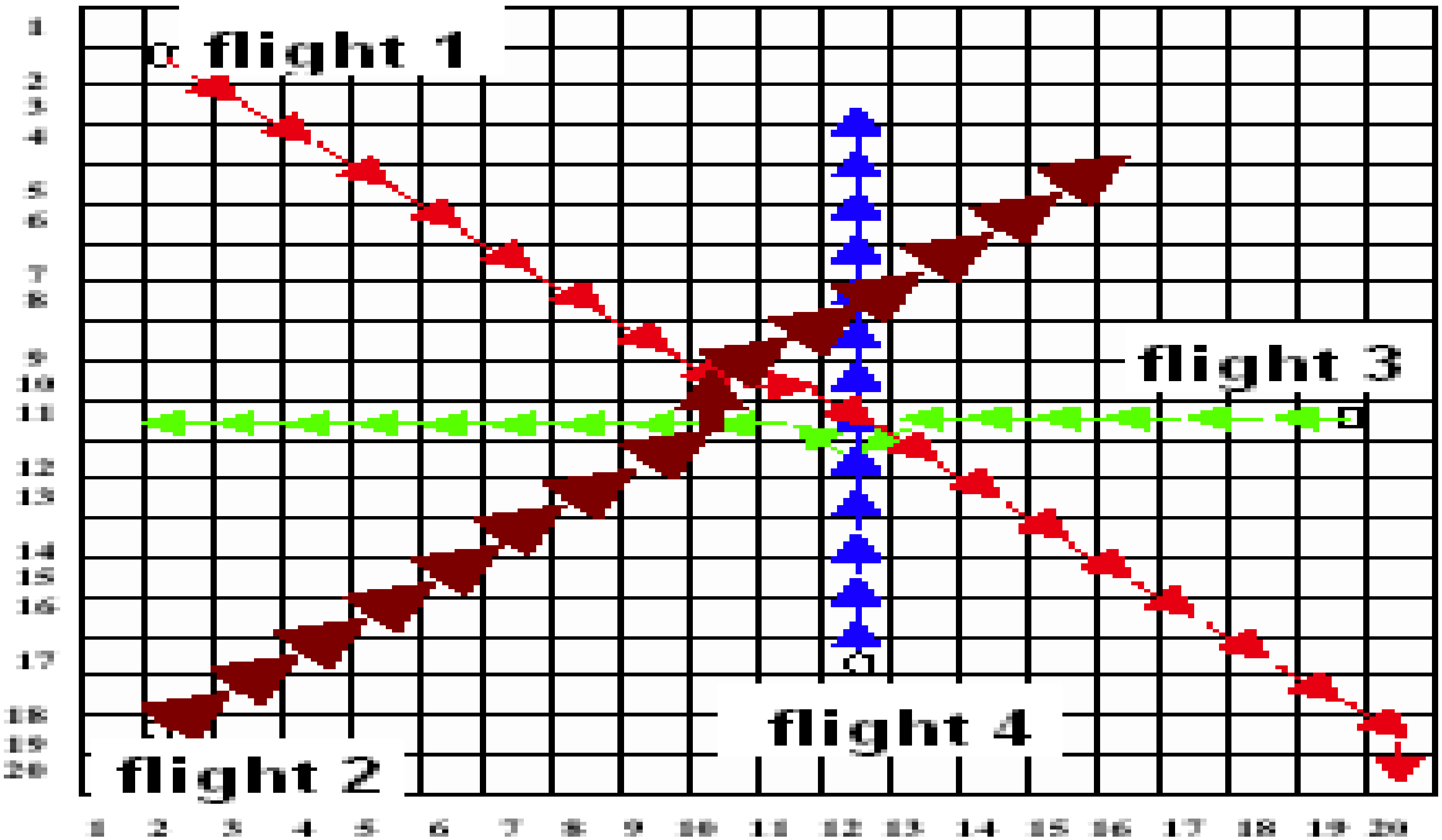


Fig. 8. Simulated Trajectories of the four flights

- This case simulates multiple aircrafts configured to cross each others path in the airspace at different time steps.

- Flight 1 is southeast bound, Flight 2 is heading towards the northeast direction Flights 3 and 4 are moving in the westward and northward directions respectively.

Fragmented Illustration of Conflict Resolution for the Four Flight Scenario

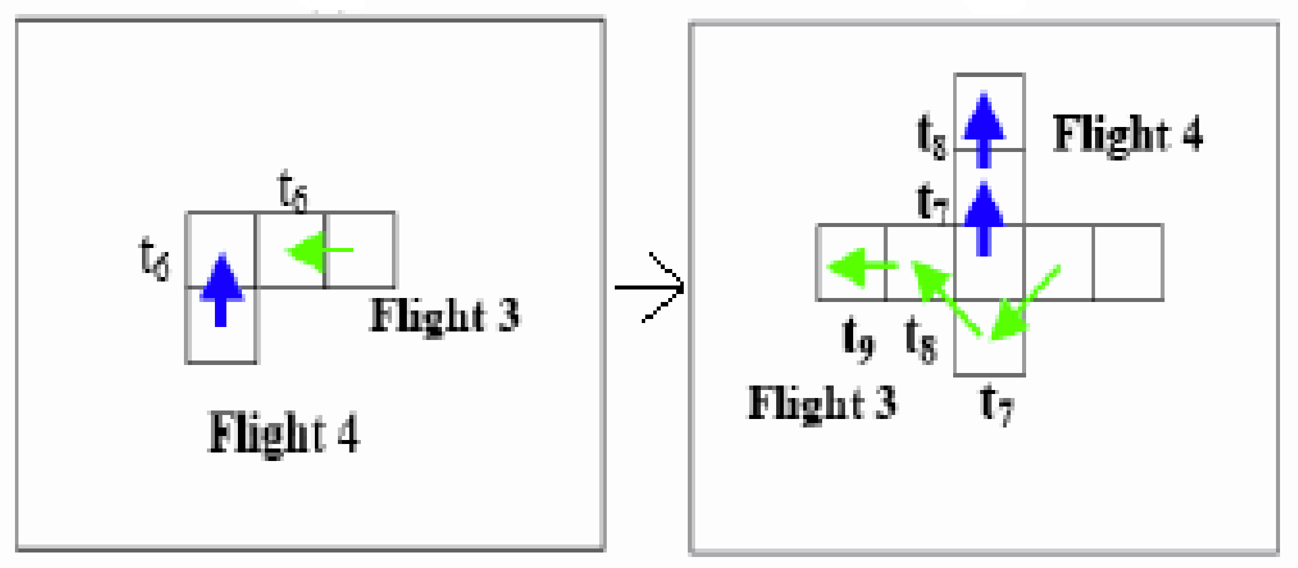


Fig. 9. Maneuvering Illustration of Flight 3 and 4.

- **Fig 9.shows Flights 3 and 4 faced with a conflict situation in the time step 6 of the simulation runs.**

- **Flight 3 being the first to move in time step 7 maneuvers properly to avoid collision with Flight 4, by first redirecting its heading towards the southwest direction and back to the eastward direction.**

- **Flight 4 aware of the maneuvering done by Flight 3 and assured of its safe forward passage continues in its vertical destination course.**

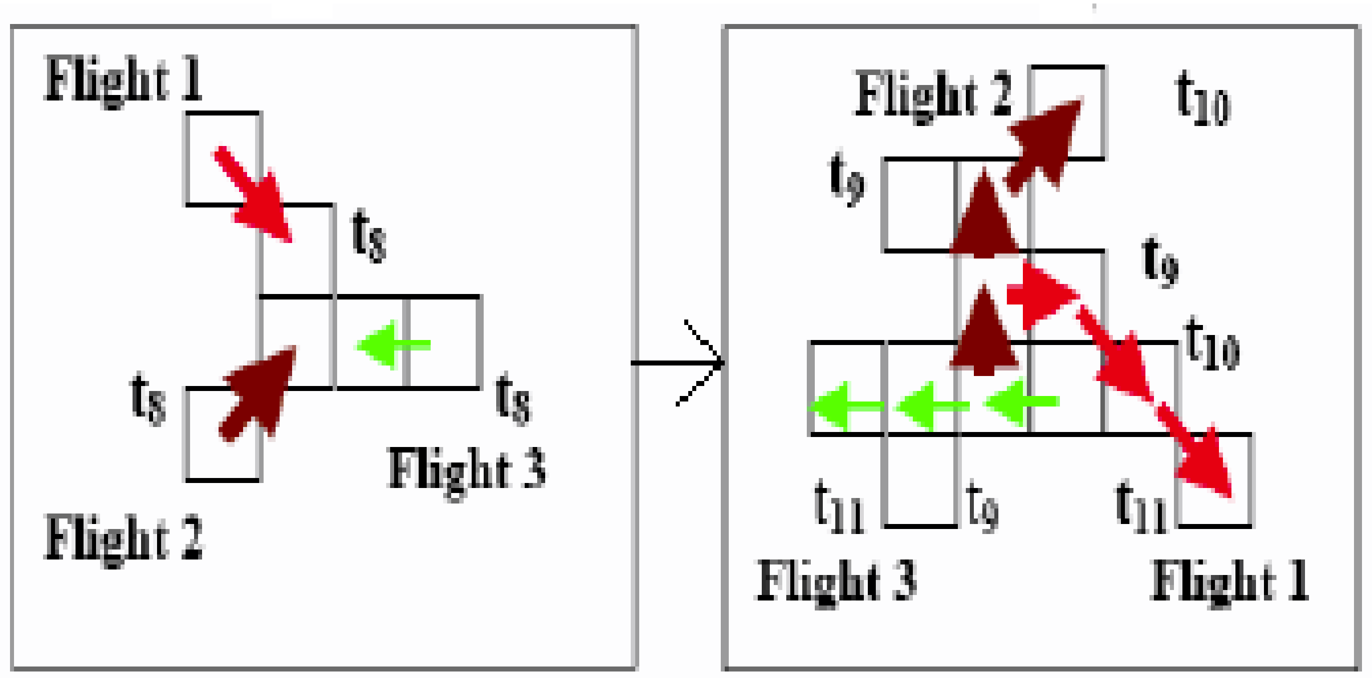


Fig. 10. Self-Spacing Maneuvering Details of flight 1, 2, and 3.

- **Time step eight has Flights 1, 2, and 3 respectively facing a conflict situation as shown in figure 10.**

- **Flight 1 moving first maneuvers in time step 9 as shown in figure 10 to avoid collision with the other two flights. Flight 2 in time step 9 moves to occupy the cell vacated by Flight 1, thereby avoiding Flight 3, which in turn moves to occupy the cell vacated by fight 2.**

- **Flight 3 continues in its optimal path heading after time step 9 to its point of destination. Flights 1 and 2 in time step 10 maneuver once more to position their headings towards their respective destination cells.**

ADVANTAGES OF DIRECTIONAL CA ALGORITHM IN AIR TRAFFIC CONTROL

- **Directional CA algorithm offers an effective en route navigation advisory information that allows for automatic maneuvering in conflict situations to ensure safe separation.**

- **The successful implementation of this concept will greatly reduce cost by cutting down the use of ground resources imbued with numerous voice communications between aircrafts and the various sectional controllers.**

- **One interesting feature of the proposed concept is that it allows for real time, one to one exchange of information and consequent automatic response between aircrafts faced with conflict situations**.

- **Errors usually attributed to untimely human judgment and inaccurate decision processes inherent in air traffic control via voice communication will extensively be eliminated.**

CONCLUDING REMARKS

- Maneuverings were very successful for all the simulation runs performed with the scenarios reported in this paper.

- The recorded shortcoming of the algorithm is in worst case scenario, when an aircraft is blocked on every side from which it has to maneuver its way out. The aircraft has to move backward and forward, based on the CA worst case rule, until all obstructions are cleared.

- The directional cellular automaton concept is best suited for the autonomous aircrafts with on-board Global Positioning System and a transponder for the exchange of information between aircrafts.

- Finally, it is worth mentioning that the directional CA algorithm could be and effective modeling tool in the en route and arrival navigation with self spacing automatic maneuvering for autonomous aircrafts.

Contact Info:

Dr. Charles Kim
Electrical and Computer Engineering
Howard University
ckim@howard.edu