Air Traffic Control System

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January 2021

Abstract

Technological developments should be used to improve human living standards and air transportation as well. The world of aviation is closing the world's distance which makes it easier for many people to go to various places around the globe. For safety matters, a safe distance will be determined that must be met by each plane to avoid conflict. Using the Boeing 737 Max 8 type, the safety distance is obtained on each side of the plane, namely the front side as far as 2,772 m, the rear side as far as 4,737 m, the right side and left side as far as 702.32 m, the top and the bottom side as far as 698.32 m. Complexity is the amount of workload carried out by Air Traffic Controller based on the number of potential conflicts in a sector in the airspace. Using the number of planes and the safety distance, the complexity of a sector in airspace can be calculated. The complexity of the sectors in the air space will be sought with three conditions, namely at any one instant time, during any interval of time, and a particular time of day.

Key words: plane, distance, complexity

Introduction

Orville and Wilbur Wright are widely known for the ones who played an important role in the history of world aviation. The Wright brothers spent more than two years testing the aerodynamics of the gliders, which later gave them the idea to create Flyer 1. Material selection is one of the crucial things in the process of making Flyer 1. When Flyer 1 debuted, it had a wingspan of 12 m, a length of 6.4 m and a height of 2.8 m. Finally, in 1903, Flyer 1 managed to fly about 12 seconds and became the first powerful, piloted flight in history.

Since then, air transportation has been more developed. Technological developments should be used to improve human living standards and the environment around them, as well as the use of technology in the aviation industry. The world of aviation today has succeeded in closing the world's distance and transporting millions of people around the world quickly and relatively cheaply. All of this is due to the advancement of plane technology which makes flying faster, more comfortable and safer. It can be seen in the image that shows the path in air transportation.

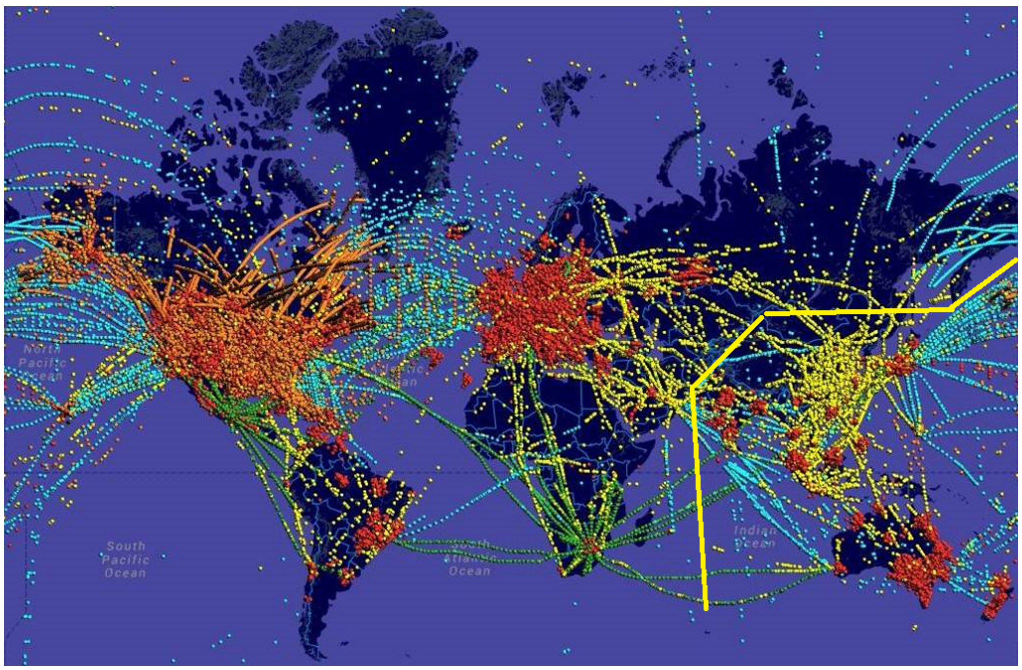

Figure 1: Air Traffic Illustration
source : Rockwell Collins

Communication technology can be used to connect the flight crew to the ground or fellow plane continuously and clearly. Navigation technology makes it possible to create a wider airspace so there could be more planes flying at once. Surveillance technology can be used to prevent potential accidents in the air.

There are several things that must be fulfilled to ensure a safe ride on air transportation, one of which is the need for an air traffic guide or usually called an Air Traffic Controller.

Figure 2: Air Traffic Control Tower
source : Airmagz.com

Air Traffic Controller or also known as ATC, is a profession that provides air traffic control services, especially plane to prevent other planes from getting too close to each other, prevent collisions between planes, and assist plane in passing through the surrounding obstacles during operation. ATC also plays a role in regulating traffic flow smoothness and provides the information that the pilots need.

The communication technology that enables the communication between pilots and the Air Traffic Controller and other ground stations is using a data link. Digital data transmission of short messages between planes and ground station is carried out using high-frequency radio technology or satellite radio.

Some of the messages that can be issued by the Air Traffic Controller are:

- Clearance requests
- Issuance of clearance permission with instruction
- Pre-departure
- Datalink ATIS
- En-route Oceanic Clearances

After mentioning that ATC has many tasks, it can be concluded that the workload of an ATC is very large. Therefore, the workload sharing mechanism of ATC is highly considered in order to reduce the boredom at work.

For this reason, the Komite Nasional Keselamatan Transportasi (KNKT) plans to add a software to the air traffic control system that can detect if there is a potential problem. This software must meet the following two requirements.

Requirement A: Can determine if two planes flying in space are too close and require intervention.

Requirement B: Can determine how complex the airspace sector from an air traffic workload perspective.

For this reason, it will also be determined the meaning of the complexity using the number of planes for a moment, in a certain time interval, on a certain day, and how the number of potential conflicts that arise affects the complexity.

Assumption

In this problem, several assumptions will be used, including:

- All planes are Boeing 737 Max 8
- All planes considered as a cylindrical tube
- All planes flying with constant speed
- All planes flying at the same altitude
- Air friction is ignored
- External impacts are ignored, such as weather

Model

The model will calculate the required distance between planes to be safe from potential conflicts. The distance between these planes is calculated from the front, rear, right side, left side, above and below.

Each plane will generate wake vortices, also known as wake turbulence. When a plane is flying, there is increased pressure on the underside of the wing and depression at the top of the aerofoil. Therefore, at the tip of the wing, there is a difference in pressure that triggers the roll of air to the rear of the wing. This vortex is also present at the end of the flaps for the same reason. At the rear of the plane, all these little vortices will mix and roll into two main vortices that rotate in the opposite direction, clockwise behind the left-wing and counterclockwise behind the right-wing if viewed from behind the plane. This vortex will affect the safety distance at the rear of the plane. The vortex of a large plane can cause damage to a nearby plane if it gets too close. To see the process of vortices, see the image below

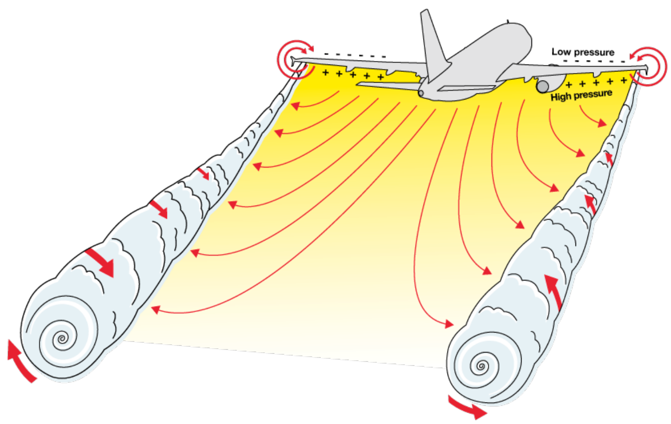

Figure 3: Development of Wingtip Vortices
source : safetyfirst.airbus.com

Another factor that can affect the safe distance of a plane is the law of bernoulli which says that the internal pressure of a fluid will decrease at the point where the speed increases. The air around the plane's wing will reduce the air pressure which makes the nearby plane accelerate to the first plane so that the forces on the right side, left side, above, and below of the plane are a combination of vortex and bernoulli.

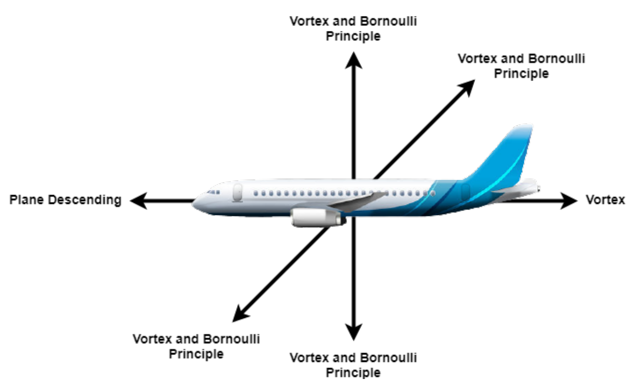

Figure 4: Model Illustration

Minimum Distance in Front of the Plane

To find the minimum distance in front of the plane, it is necessary to assume that 12 s is the time needed for the plane to avoid objects in front of it. So by using the speed of the Boeing 737 Max 8, which is 231 m/s so that the minimum distance from the front of the plane is 2,772 m.

Minimum Distance Behind the Plane

The safety distance behind the plane will be affected by the vortex generated from the plane. Using the Boeing 737 Max 8 type, a vortex will be generated from it's wing which has a diameter of 11.32 m with a vortex rotation speed of 44.37 m/s. This vortex will start to sink at a speed of 1.53 m/s and will disappear if the distance from the plane is 3 NM (Nautical Mile) or 5,556 m long. The vortex generated by the plane has a diameter of 11.32 m, so the volume of air that can be transported is 6.678 m^3, with the density of air at an altitude of 10,000 m is 0.414 kg/m^3 we can calculate the weight of the air is 2.764 kg if the plane is on the vortex.

We can divide equilibrium into two types, namely static and dynamic equilibrium. Dynamic equilibrium is when an object remains in constant motion both in translation and rotation. In rotational motion, angular momentum is linear momentum in the axis of rotation. Angular momentum is denoted by L where $L = m\omega r^2$ where m is mass, ω is the angular velocity and r is the distance of the particle to the axis of rotation. Meanwhile, the inertia I is obtained as $I = mr^2$ so that we get $L = I\omega$. Finally, we can get

$$L_{air} = I_{air}\omega_{air} = I_{plane}\omega_{plane} = L_{plane} \tag{1}$$

We can calculate the air inertia by

$$I_{air} = \frac{mr^2}{2} = 0.5 \times 2,764 \times (5.6)^2 = 4.42 \times 10^4 kg \cdot m^2$$

Given that the velocity of the vortex is 44.37 m/s and the circumference is 35.56 m, it takes 0.8 s to do a full rotation, which means that the initial angular velocity is 7.85 rad/s. The time taken for the vortex to disappear is 24.05 s. The angular acceleration can be calculated with

$$\alpha = \frac{\omega_f - \omega_i}{t} = \frac{0 - 7.85}{24.05} = -0.33 rad/s^2$$

We can find the angular velocity at $t = d/231$ where d is the distance the plane has travelled. Using this, it is obtained

$$\alpha = \frac{\omega_f - \omega_i}{t} = \frac{\omega_f - 7.85}{d/231} = -0.33 rad/s^2$$

$$\omega_f = -1.42 \times 10^{-3} d + 7.85 rad/s$$

Assuming our plane is a cylindrical tube, then to calculate the inertia of the plane leading to the vortex using the Boeing 737 Max 8 type, it is obtained

$$I_{plane} = mr^2 = (71,700)(2)^2 = 2.868 \times 10^5 kg \cdot m^2$$

Assume the initial angular velocity is 0 and the plane cannot turn more than 5 ° (0.0873 rad) in 1s. Using a accelerated linear motion on rotation, angular acceleration can be found, so that it is obtained

$$\theta = \omega_i t + \alpha t^2/2$$

$$0.0873 = \theta = 0 + \alpha 1^2/2$$

$$\alpha = 0.1746 rad/s^2$$

Also, the angular velocity can be calculated using accelerated linear motion

$$\omega_f^2 = \omega_i^2 + 2\alpha\theta = 2(0.1746)(0.0873),\ \omega_f = 0.1746 rad/s$$

It can be calculated the safe distance behind the plane using equation (1), which is

$$(4.42 \times 10^4)[(-1.42 \times 10^{-3})d + 7.85] = (2.868 \times 10^5)(0.1746)$$

$$d = 4,737m$$

So it is obtained the safe distance behind the plane is 4.737 m.

Minimum Side Distance

The velocity of the vortex is 44.37 m/s with an acceleration of -1.71 m/s^2. Using straight motion to change with order, is obtained $v_f^2 = v_i^2 + 2ad = (44.37)^2 + 2(-1.71)(d) = 1.97 \times 10^3 - 3.42d$. The safety distance on the side apart from being affected by the vortex is influenced by bernoulli. It is assumed that the plane flies at the same altitude so that the law of bernoulli can be written as

$$P_i + \frac{\rho_i v_i^2}{2} = P_f + \frac{\rho_f v_f^2}{2} \tag{2}$$

Using an initial velocity of 0, the density of air is 0.414 kg/m^3, and a pressure of 2,650 Pa, we can find the final pressure using

$$2,650 = P_f + \frac{(0.414)(1.97\times10^3 - 3.42d)}{2}, P_f = 2,240 + 0.708dPa$$

$$\Delta P = 410 - 0.708d$$

Minimum Horizontal Side Distance

We assume the shape of our plane is a cylindrical tube. Given that the length of the Boeing 737 Max 8 is 39.5 m and the width of 4 m without the wings, it can be calculated that the surface area is $\pi rl = 248m^2$. Using $P = F/A$, it can be obtained

$$410 - 0.708d = F/248, F = 1.017 \times 10^5 - 176d$$

Given that $F = m \cdot a$, assuming the acceleration is 0.1 m/s^2, it can be calculated

$$1.017 \times 10^5 - 176d = (7.17 \times 10^4)(0.1), d = 538$$

Then, the safety distance on the horizontal side is d + Vortex Width + 0.5 (Wing Length) + Radar Inaccuracy. Using this we get a safe distance of $538 + 11.32 + 0.5(36) + 135 = 702.32$ m.

Minimum Horizontal Side Distance

It is known that the wing area of the Boeing 737 Max 8 is 127 m^2. It can be calculated that the surface area is 0.5 (cylindrical tube area) + wing area = 375 m^2. Using $P = F/A$, it can be calculated

$$410 - 0.708d = F/375, F = 1.54 \times 10^5 - 266d$$

If $F = m \cdot a$ assuming the acceleration is 0.1 m/s^2, it can be calculated

$$1.54 \times 10^5 - 266d = (7.17 \times 10^4)(0.1), d = 552$$

Then, the safety distance on the vertical side is d + Vortex Width + Radar Inaccuracy. Using this, it is obtained a safe distance of 552 + 11.32 + 135 = 698.32 m.

Illustration of Minimum Airplane Distance

The illustration of safe distances seen from above and from the side view as follows,

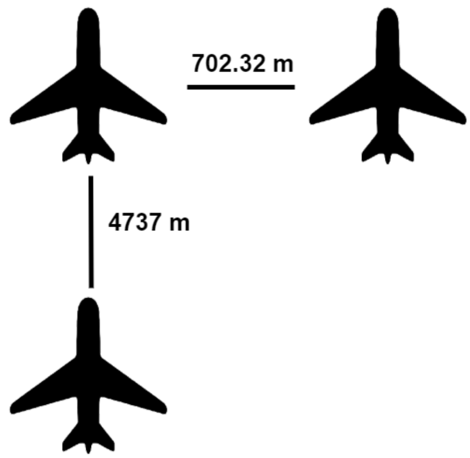

Figure 5: Top view of safe distances

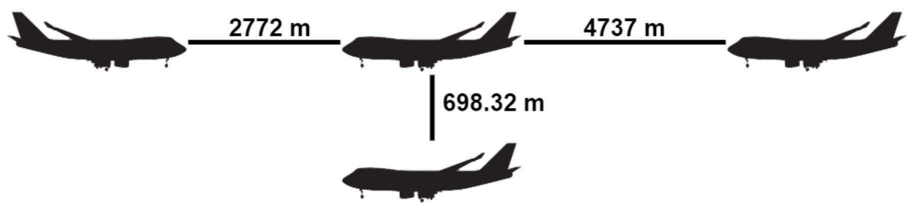

Figure 6: Side view of safe distances

Complexity

Define airspace as a three-dimensional space above the earth's surface. Complexity is defined as the amount of workload required by an Air Traffic Controller or ATC. ATC workload is determined by the number of potential conflicts in a sector in airspace. To determine the potential for conflict in a sector in airspace, the location and safe distance of the plane are used.

Assuming the planes fly at the same altitude, we can view airspace in two dimensions. Airspace of a certain size can be represented in a matrix. Suppose M_{ij} is a matrix of airspace in the i-th latitude and j-th longitude sector, where $m \in M$ represents a block of airspace of 4 m $\times$ 4 m. Thus, based on the Boeing 737 Max 8 size of 39.5 m $\times$ 4 m, this plane can be represented as a vector of 10 $\times$ 1 in the M matrix.

To model the complexity of a plane, a predetermined safe distance from a plane is used. Safe distance for the front, rear, and sides of the plane. Define the safety zone of a plane as the area around the plane with the dimensions at the front, rear, and sides of the plane that do not exceed the safe distance from the plane. To simplify the model, the safety zone is made 10x smaller than the plane safe distance. Thus, the configuration of the safety zone of the plane in airspace is as follows.

- Front safety distance: 70 block
- Rear safety distance: 120 block
- Sides safety distance: 18 block

Suppose that one sector of airspace is a square with a size of 16 km^2. This air sector is represented by a M_{ij} matrix of 100×100 for any i and j. An example of an illustration of airspace with 32 sectors is as follows.

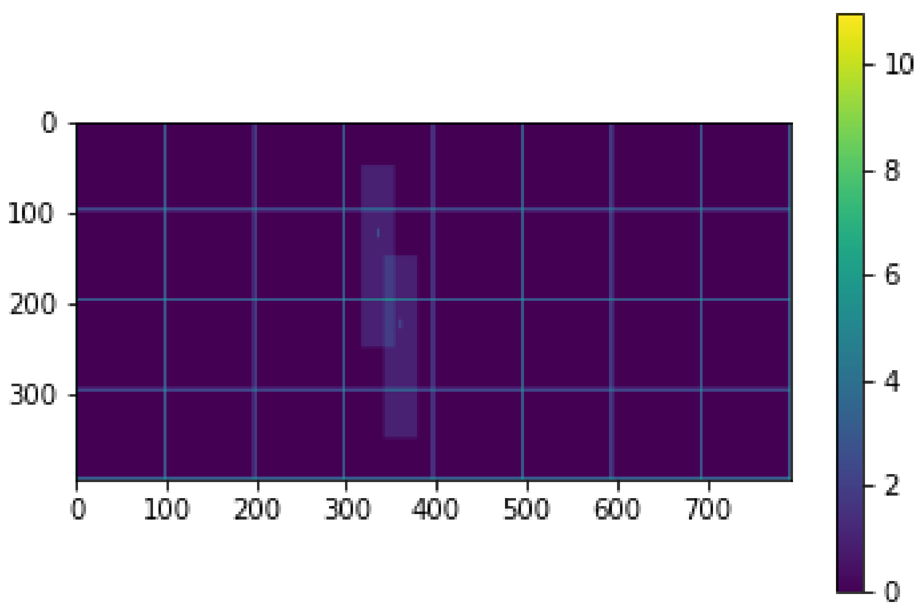

Figure 7: Example of an Airspace with 32 Sectors and 2 planes

Complexity at Any One Instant

The existence of a plane in one sector of airspace will certainly limit the moving space for other planes because each plane has it's own safe zone. Sections of two or more parts of the plane safety zone are represented as potential conflicts that occur in the airspace. So that the more plane are in one airspace sector, the more complex the airspace sector will be. To calculate the complexity of an airspace sector at any one instant time, the safety zone of the plane will be used according to these following weights.

- Plane: 10 unit of complexity per block
- Plane safety zone: 1 unit of complexity per block

For example, suppose there are plane A and plane B. If in an airspace sector there is a safety zone slice between plane A and B, then the slice will be worth 2 units of complexity per block. If the coordinate block of the plane is in the safe zone of another plane, the block will be worth 11 (10 units of complexity from plane A + 1 units of complexity from the safe zone of plane B) units of complexity.

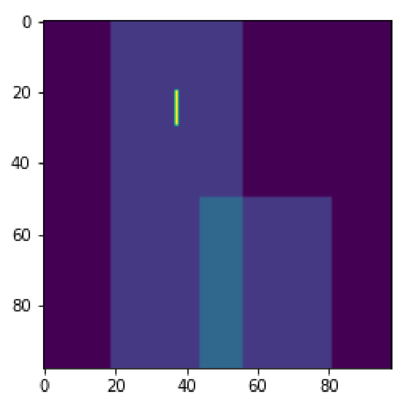

Figure 8: Visualization of Airspace 2nd Latitude 4th Longitude

The complexity of an airspace sector latitude i and longitude j is denoted by $c_{i,j}$ which is the sum of all complexity weights for each block in the airspace sector on i-th latitude and j-th longitude, that is

$$c_{i,j} = \sum_j \sum_k m_{j,k},\ m_{j,k} \in M_{i,j}$$

For example, $M_{2,4}$ contains elements with the following values.

- 4240 blocks with 1 complexity unit
- 576 blocks with 2 complexity unit
- 10 blocks with 5 complexity unit

So, it is obtained the complexity of $M_{2,4}$ is

$$c_{2,4} = 4240 + (576 \times 2) + 10 \times 5 = 5442 \text{ complexity unit}$$

Furthermore, we can obtain the relative complexity value of an airspace sector by scaling, which is dividing the value of the complexity of an airspace by the sector size of the airspace (in this case 100×100) which represents the entire block of that airspace sectors has a value of 1 complexity unit. So for the case of $M_{2,4}$ the value of the relative complexity is $c_{2,4} = \frac{c_{2,4}}{(1\times100\times100)} = 0.5442$. The higher the complexity value of an airspace sector, the greater the potential for conflict in the airspace sector.

Complexity during Any Interval of Time

Of course, certain airspace sectors will change over time due to plane moving into, within, and leaving an airspace sector. By doing discretization for a certain time interval, the complexity of the airspace sector can be calculated at that time interval. For example, to calculate the complexity of the airspace sector at 5 minutes intervals, it can be discretized to 5×1 minute, so that the complexity of the airspace sector will be calculated by 5 times and the condition of the airspace sector including the coordinates of the plane and its safety area is updated once every minute. It is illustrated as follows

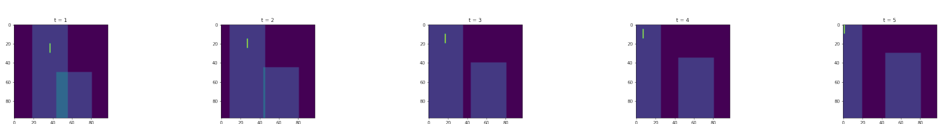

Figure 9: Visualization of An Airspace Sector for Five Interval of Time

By calculating each $c_{i,j,t}$, which is the complexity of the airspace sector ith latitude, j-th longitude on the tth timeframe to the T-th timeframe, where $t = \{0, 1, 2, ...T\}$, we get the airspace sector complexity $M_{i,j}$ at a certain time interval is

$$\sum_t c_{i,j,t}, t = \{0, 1, 2, ...T\}$$

For example, the complexity on $M_{2,4}$ for 5 timeframes are presented as follows.

- At $t = 1, c_{2,4,1} = (1 \times 4240) + (2 \times 576) + (5 \times 10) = 5442$
- At $t = 2, c_{2,4,2} = (1 \times 5365) + (2 \times 106) + (5 \times 10) = 5627$
- At $t = 3, c_{2,4,3} = (1 \times 5664) + (5 \times 10) = 5714$
- At $t = 4, c_{2,4,4} = (1 \times 4869) + (5 \times 10) = 4919$
- At $t = 5, c_{2,4,5} = (1 \times 4466) + (5 \times 10) = 4516$

So that the complexity of the airspace sector represented on the $M_{2,4}$ matrix on the timeframe $t = \{1, 2, ...T\}$ is

$h_{2,4} = \sum_t c_{2,4,t} = 5442 + 5627 + 5714 + 4919 + 4516 = 26218$ complexity unit

Complexity a Particular Time of Day

On a certain day, there is a possibility that a sector of airspace is passed through by various types of plane and moves into, within, and leaves an air space sector. By expanding the concept of complexity during any given interval of time, we can calculate complexity during a particular time of day in the $M_{i,j}$ airspace sector, namely

$$d_i = c_{i,j,t}, \text{ with } t = \{0, 1, 2, ...T\}$$

Of course, the T for a given day can be made larger than the T used at certain time intervals to represent a more representative level of complexity. For example, if $T = 24$ means that in one day the complexity of an airspace sector will be renewed every 1 hour, whereas if $T = 96$ then the complexity of an airspace sector will be renewed every 15 minutes.

Summary

MINISTRY OF TRANSPORTATION
KOMITE NASIONAL KESELAMATAN TRANSPORTASI
DIVISION OF AIR TRAFFIC CONTROL

FOR : Soerjanto Thahjono, KNKT Chairman
SUBJECT : Summary of Air Traffic Control System

To be able to build software that will be used by KNKT, it is necessary to determine what things have the potential to cause conflict in the airspace. We define a potential conflict as something that can cause an air accident. By assuming there is no weather influence and no human error, air accidents can occur due to the lack of the minimum distance required for the plane. In this paper, using the Boeing 737 Max 8 type, we have determined the minimum distance the plane needs on each side so the potential for air accidents can be reduced. For example, for a Boeing 737 Max 8, it needs 2,772 m on the front side, 4,737 m on the rear side, 702.32 m on the right side and left side, and 698.32 m on the top or bottom side. In a similar way, the minimum distance needed for each side can be calculated for various types of aircraft.

This minimum distance will be used to find the safe zone of the plane in the airspace. If the safe zone of a plane interrupted by another airspace object, the potential for conflict will increase. The software will determine the safe zone of each plane. To determine the software workload in calculating the safe zone, we assigned a weight for each condition that occurs in airspace sectors, such as the location of the planes, the number of planes in an airspace sector, and the safety zone of each plane in the airspace sector. We define the complexity of the airspace sector as the sum of the weights for each condition in an airspace sector. It means that the software workload is determined by how the software calculates the complexity for each airspace sector. To determine the complexity of each airspace sector, the calculations are carried out quite quickly because it uses simple arithmetic operations.

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