ARTIFICIAL INTELLIGENCE FOR SUSTAINABLE AIR TRANSPORTATION

Technology for a post-COVID-19 World of Aviation
ACKNOWLEDGEMENTS

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INTRODUCTION TO NTU COLLEGE OF ENGINEERING

NTU College of Engineering (CoE) was established in 2001 to integrate the diverse engineering disciplines found within the university and to promote interaction among the individual engineering schools. Today, CoE comprises six engineering schools:

- School of Chemical and Biomedical Engineering (SCBE)
- School of Civil and Environmental Engineering (CEE)
- School of Computer Science and Engineering (SCSE)
- School of Electrical and Electronic Engineering (EEE)
- School of Materials Science and Engineering (MSE)
- School of Mechanical and Aerospace Engineering (MAE)

One of Singapore’s premier tertiary institutions, we are ranked No. 8 for the Engineering and Technology category in Quacquarelli Symonds (QS) World University Rankings 2020. We are also one of the world’s largest engineering colleges.

As a university, we go beyond mere knowledge creation and discoveries. Indeed, we are distinguished by our powerful focus on translating knowledge into practical innovations and future-ready solutions. In pursuit of this goal, we collaborate closely with local and international companies and institutions to develop cutting-edge solutions for real-world problems. This collaboration takes a number of forms, including corporate laboratories, joint laboratories and other programmes.

We invite you now to join us in capability building, innovation and talent development. As our strategic partner, you will ride the waves of technological breakthroughs and industry transformation and emerge ahead of the pack.
According to the forecasts by International Civil Aviation Organisation (ICAO), the global passenger traffic, at the current growth rate of 4.3% annually, will double by 2035*. In 2018 alone, the air transportation system served nearly 8 billion passengers and operated over 90 million flights worldwide. The Asia-Pacific region, contributing to more than a third of these passengers, is estimated to have the highest growth rate at 7.2% annually up to 2035*. However, the latest estimates from the International Air Transport Association (IATA) indicate a severe impact on aviation due to the COVID-19 crisis in the Asia-Pacific region. IATA and ICAO analyses show that the COVID-19 crisis will see global airline passenger revenues drop by 55% compared to 2019. Airlines in Asia-Pacific will see the largest revenue drop of US$113 billion in 2020 compared to 2019 and a 50% fall in passenger demand in 2020 compared to 2019. Undoubtedly, the aviation industry will eventually recover and the challenges of increasing delays, prolonged airspace congestion, flight cancellations, increasing air traffic incidents, Air Traffic Controller (ATC) workload issues and environmental concerns such as noise and emissions will emerge again. Therefore, there is an imminent need and opportunity to recalibrate our research directions and operational strategies to sustain the growth of air transportation.

Artificial Intelligence (AI) and Data Analytics techniques, such as machine learning, neural networks, swarm intelligence, predictive analytics, have demonstrated the potential to address complex problems in this domain. New research findings and insights into Explainable and Robust AI, dealing with “how machines learn” and “how machines can perform higher-order cognitive tasks”, present an extremely potent toolbox to manage and sustain the air traffic growth. In view of global privacy laws like the General Data Protection Regulation (GDPR) and Personal Data Protection Act (PDPA), privacy-preserving data analysis and machine learning is not just an option, but a mandate. State-of-the-art research outcomes in cybersecurity and privacy will thus be a gamechanger in secure aggregation, mining, and analysis of data available in abundance from every sector of the evolving air transportation landscape.

Nanyang Technological University (NTU Singapore) is an established world leader in AI and air transportation research. Air Traffic Management Research Institute (ATMRI) is a joint research institute established by the Civil Aviation Authority of Singapore (CAAS) and NTU in 2013 to conduct dedicated research in air traffic management. Since its establishment under the School of Mechanical and Aerospace Engineering (MAE), ATMRI has conducted ground-breaking research in addressing the challenges faced by air transportation, including the design and development of a hybrid AI-Human Air Traffic Control (ATC) paradigm that can significantly contribute to the next generation of air traffic management systems. ATMRI is also designing a suite of AI algorithms and machine learning models that can augment human tasks in air traffic control, assisting air traffic controllers to perform higher-order cognitive tasks like strategic air-traffic flow management. ATMRI has developed practical, implementable AI algorithms backed by sound methodologies that aim to balance demand and capacity while addressing safety and environmental concerns. The search for these intelligent algorithms has provided new insights and approaches into solving such problems. This has attracted significant research investment from the government and the industry in the area of AI for air traffic management.

The School of Computer Science and Engineering (SCSE), under the College of Engineering (CoE) at NTU, is a leader in AI and cybersecurity; running numerous funded projects in automation, learning, security and privacy. Collaborations between ATMRI, SCSE and MAE, aim at wider adoption of robust privacy-preserving AI tools and techniques for sustainable air traffic management.

* Pre-COVID-19 figures.
DEAN’S MESSAGE

At NTU’s College of Engineering (CoE), our vision is to be the hub for knowledge, capabilities, and partnerships, in Singapore and worldwide. Beyond knowledge creation and discoveries, we strongly believe in translating knowledge into applied research outcomes that can solve real-world problems. To this end, we actively pursue interdisciplinary research with researchers from other colleges in NTU, peer institutions, government agencies and industries.

This Technology Primer series is specially commissioned by the management of CoE. Our goal is to empower existing and potential partners in the industry and government to understand more about the latest technological trends and developments. Put together by multidisciplinary research teams with good track records in our college, the series also documents the cutting-edge technologies we have developed in recent years as well as the key capabilities and research facilities we house. We hope that this series will serve as a good resource for partners as they navigate the waves of major technological breakthroughs and initiate future collaborations with us.

I invite you to join us in our pursuit to innovate, advance and transform our world, for a better tomorrow.

Professor Louis Phee
Dean
College of Engineering

To view more technology primers developed by CoE, please go to our webpage: https://coe.ntu.edu.sg/Research/ResearchImpact/Pages/TechnologyPrimers.aspx
# TABLE OF CONTENTS

1. AIR TRANSPORTATION AS SYSTEM OF SYSTEMS  
   
2. CHALLENGES TO GLOBAL AND SINGAPORE AIR TRANSPORTATION  
   
3. TECHNOLOGY SURVEY  
   
4. MARKET AND TECHNOLOGY TRENDS  
   
5. RESEARCH AND DEVELOPMENT AT THE COLLEGE OF ENGINEERING  
   
6. CAPABILITIES AND KEY RESEARCH FACILITIES AT COE  
   
7. OPPORTUNITIES FOR COLLABORATION  
   
REFERENCES

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# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Annual World Airport Traffic Report 2019</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>Asia-Pacific leading the regional traffic growth</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>Air Traffic demand (passenger growth) in first quarter 2020</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>Southeast Asia airport network</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>Changi Airport aircraft departures and arrivals trends</td>
<td>17</td>
</tr>
<tr>
<td>6</td>
<td>Airborne delays for flight coming to Southeast Asia</td>
<td>19</td>
</tr>
<tr>
<td>7</td>
<td>NTU’s hybrid Human-Al Air Traffic Management paradigm</td>
<td>27</td>
</tr>
<tr>
<td>8</td>
<td>The hybrid AI-Human Air Traffic Management system for air traffic conflict resolution</td>
<td>28</td>
</tr>
<tr>
<td>9</td>
<td>Air traffic controller under MRI scanner identifying air traffic conflicts through an automation aid</td>
<td>29</td>
</tr>
<tr>
<td>10</td>
<td>Singapore airspace with complex network of airways</td>
<td>30</td>
</tr>
<tr>
<td>11</td>
<td>Critical nodes and links in Singapore airspace network</td>
<td>31</td>
</tr>
<tr>
<td>12</td>
<td>Framework for real-time detection of unstable approaches based on A-SMGCS data</td>
<td>32</td>
</tr>
<tr>
<td>13</td>
<td>Machine-learned hotspots at Changi Airport taxiways</td>
<td>34</td>
</tr>
<tr>
<td>14</td>
<td>Data-driven prediction of taxi timings at Changi Airport taxiways</td>
<td>35</td>
</tr>
<tr>
<td>15</td>
<td>Data-driven prediction of arrival timings by intelligent clustering of trajectory data</td>
<td>36</td>
</tr>
<tr>
<td>16</td>
<td>Identification of delay features in terminal airspace with holding patterns</td>
<td>36</td>
</tr>
<tr>
<td>17</td>
<td>Delay propagation due to departure delays</td>
<td>37</td>
</tr>
</tbody>
</table>
SECTION 1:

AIR TRANSPORTATION AS SYSTEM OF SYSTEMS

Air transportation system has evolved into a multi-dimensional, highly distributed, yet interdependent system, which interacts with a multitude of global and regional economies.

It is a complex socio-technical system of systems, which involves non-linear and non-hierarchical interactions between human operators, technical systems, and procedures with in-built feedback loops. The complex system behaviour leads to amplification of disturbances due to inherent uncertainties, and demonstrates phenomena such as emergence, adaptation and operations on the edge of chaos.

Typical system-level problems in this domain are unstructured, requiring proper exploratory analysis, and problem structuring tools. Moreover, the non-linear, stochastic and time-dependent interdependency among the components in the system make the classical assumptions of linearity, homogeneity and normally distributed observations, obsolete.

Artificial Intelligence (AI) and Data Analytics (DA) techniques, such as machine learning, multi-agent systems, evolutionary computation, swarm intelligence, neural networks and predictive analytics have demonstrated the potential to address complex problems in this domain where traditional methodologies were ineffective or infeasible. New research findings and better insights into “how machines can learn” and “how machines can perform higher-order cognitive tasks”, can make these techniques a very powerful tool to manage and sustain air traffic growth.

Figure 1: Annual World Airport Traffic Report 2019 [1]

THE RISE OF AIR TRANSPORTATION

According to the Airports Council International (ACI) World Airport Traffic Report 2019, passenger numbers were estimated to have reached 8.8 billion in 2019; growing by 6.4% compared to 2018 (pre COVID-19 figures). While growth moderated slightly compared to 2018, passenger traffic remained resilient in the face of the global uncertainties besetting many economies.

The COVID-19 pandemic has caused a significant impact on the aviation industry due to the travel restrictions as well as decline in passenger travel demand. The latest estimates indicate the possible COVID-19 impact on scheduled international passenger traffic for the entire 2020. A delayed recovery may lead to an overall reduction ranging from 68% to 71% of seats offered by airlines—an overall reduction of 1,108 to 1,524 million passengers and approximately US$194 to 269 billion potential loss of gross operating revenues of airlines.

The Asia-Pacific region was predicted to be the biggest driver of air traffic demand with more than half of the new passenger traffic. This shift would be driven by a combination of continued robust economic growth, improvements in household incomes, and favourable population and demographic profiles.

However, due to the unfolding COVID-19 crisis, ICAO estimates that there can be an overall reduction of 44% to 80% of international passengers in 2020 compared to 2019. Furthermore, ACI estimates indicate that airports will suffer an approximate loss of over 50% of passenger traffic or over US$97 billion in airport revenues in 2020 compared to business as usual.

While this unfortunate set of events may suggest a brief pause for the air transportation industry, it could also be an opportunity for the use and adoption of technology for efficiency and safety.
RESEARCH EFFORTS ON MANAGING THE IMPACT OF COVID-19 ON AIR TRANSPORTATION:

The air transportation industry is facing its deepest crisis ever in history. The COVID-19 pandemic has caused a significant impact on the air transportation industry due to current travel restrictions as well as declines in passenger travel demand. The aviation sector bears the major consequences of the COVID-19 pandemic as its primary business is the transport of people and goods across the globe for travel, tourism, business, and trade.

According to an analysis conducted by the International Civil Aviation Organisation (ICAO) on the economic impact of COVID-19 on aviation, in the month of March 2020 alone, passenger numbers have plunged by 54% or 198 million, due to a reduction in load factor [4]. This lack of demand in air traffic has caused severe financial pressures on all stakeholders in the aviation sector. In the first quarter of 2020, airlines are estimated to lose USD 28 billion in revenues, and airports and air navigation service providers have lost around USD 8 billion and USD 824 million, respectively [3].

Air traffic demand collapses (passenger growth, YoY)

![Image showing air traffic demand collapses](source: ICAO ADS-B operational data)

Figure 3: Air Traffic demand (passenger growth) in first quarter 2020 [3]

In managing the impact of COVID-19 on air transportation, a significant amount of work is in progress by researchers and the aviation industry. At the earlier phase, the studies have mainly focused on understanding the correlation between air transport and the spread of COVID-19 [5, 6] to inform the recommendations of better policies to control the pandemic. Recently, with the resumption of air travels, the research has shifted slightly to estimating the risk of transmission for international flights [7] and appropriate approaches to reduce it.

To prevent the transport of infected people as far as technically possible, the efficacy of screening measures such as temperature-taking and declaration of symptoms were investigated [8]. In addition, the development of appropriate capacities for rapid, reliable, and cost-effective COVID-19 testing before (or after travel) was also studied [9]. To further increase the safety of passengers and flight crew, minimising the risk that undetected infected persons transmit the virus to other passengers during the travel have been considered. Fortunately, there have been many lessons which can be learned from previous outbreaks of communicable diseases in the aviation industry [10-12].

The studies have shown that in-flight transmission rate is generally low. It was proposed that with appropriate physical distancing, the risk of transmission during flight can be reduced significantly. As one of the main operations with a high risk of transmission, boarding processes under COVID-19 flying restrictions also need to be investigated and adapted [13]. Moreover, updates in reducing the risk of contact such as limiting the number of hand luggage items or the use of a second door for boarding have also been investigated [14]. As emphasised in a recent report of IATA: "The resumption of international flights will require a number of hurdles to be crossed", and for that more research is required and anticipated.
SINGAPORE: THE AVIATION HUB OF SOUTHEAST ASIA

In Southeast Asia, Singapore has maintained its leadership in aviation and air transportation over the years. The Singapore Changi Airport, commonly known as Changi Airport, has emerged as a major airport hub for the region. It has witnessed high traffic growth for the years 2004 and 2011.

Specifically, the year 2004 saw an annual increase of almost 20% for arrivals and departures over the previous years due to arrival of low-cost carriers, Tigerair and Jetstar, which started operations in late 2003 and 2004, respectively. Similar trends were observed in 2011 with a year-on-year increase of approximately 15% in arrivals and departures with the introduction of Scoot in 2011.

As the region’s premier gateway, Changi Airport registered a record number of 66.3 million passenger movements in FY2018/19.

With more than 100 airlines connecting Singapore to 380 cities worldwide, Changi Airport is now the world’s seventh busiest airport for international traffic, handling about 7,400 flights every week, or about one flight every 80 seconds. Indonesia continues to rank as Changi Airport’s largest country market, followed by China, Malaysia, Australia and Thailand.

However, as COVID-19 pandemic continues to have a severe impact on air travel with border controls and travel restrictions remaining in place around the world, passenger movement at Changi Airport is severely affected.

Figure 4: Southeast Asia airport network weighted according to degree centrality, where bigger dots imply higher connectivity [15]

Figure 5: Changi Airport aircraft departures and arrivals — change year-on-year with spikes in 2004 and 2011 due to the introduction of new airline models [16]
SECTION 2: CHALLENGES TO GLOBAL AND SINGAPORE AIR TRANSPORTATION

A fast, efficient and inexpensive means of transport is fundamental to globalisation and socio-economic development of the society. According to ICAO’s forecasts, global passenger traffic will double by 2035* with the current growth rate of 4.3% annually. In 2018 alone, the air transportation system served nearly 8 billion passengers and operated over 90 million flights worldwide, with the Asia-Pacific region contributing more than a third of these passengers.

However, this growth is unsustainable as evidenced by increasing delays, flight cancellations, airspace congestion, taxiway incidents, ATC workload and environmental concerns. Furthermore, continued growth in air traffic, reduced robustness to external conditions such as weather, and increased safety and environmental concerns have brought new challenges to air navigation service providers, airlines, airports and other stakeholders. Therefore, there is an imminent need for new research directions and operational strategies to sustain the growth of air transportation.

These challenges, if not addressed in time, may disrupt the entire air transportation system, leading to broader economic and social problems. A fundamental change is required in the way we design, manage and run our air traffic management system for it to be sustainable.

*Pre COVID-19 figures

DELAYS AND CONGESTION

The continued air traffic growth has resulted in severe constraints on existing communication, navigation and surveillance systems, as well as infrastructure — both in the air and on the ground. For example, there will be a heavy voice frequency congestion, given the very limited frequencies available for Area Control Centre (ACC). Increased air traffic is also challenging the cognitive limits of human ATC in managing higher traffic densities for prolonged duration.

Limited airspace capacity results in delays as well, especially in terminal airspace. This is particularly evident in the European airspace, where a 14% increase in the en-route (overflying) traffic in 2018 led to a phenomenal increase of 279% in overall flight delay, indicating that we have reached a tipping point in airspace capacity.

Figure 6: Airborne delays increased significantly as compared to increase in number of flights in 2018 [17]
A recent European Commission report comparing air traffic management in the United States and Europe found in 2017, that despite the United States controlling nearly 50% more flights (15.3 million in the United States versus 10.4 million in Europe), “the total number of flights with reportable delay was 387,000 in Europe versus 258,000 in the United States. This means that 50% more flights were delayed in Europe than in the United States”, due to the fragmented system in Europe. The Southeast Asia region also suffers from a similarly fragmented airspace and is increasingly prone to congestions leading to unsustainable delays.
SECTION 3: TECHNOLOGY SURVEY

The emergence and applicability of big data, powerful learning algorithms and high computing power available on board an aircraft and in ground air traffic control centre, is offering a whole new approach to challenges faced by air transportation.

A) THE PARADIGM SHIFT TO ARTIFICIAL INTELLIGENCE (AI) AND DATA ANALYTICS (DA)

This paradigm shift brings new research challenges in AI, machine learning, and DA in processing, filtering, denoising, grouping, clustering, deriving and learning knowledge from this data, for autonomous air and ground systems and collaborative man-machine critical decision making. With the increasing availability of air traffic data and passenger movements as well as powerful computing resources, machine learning methods have emerged as promising methods for solving air traffic management problems such as runway and taxiway optimisation, aircraft sequencing, trajectory prediction, aircraft performance predictions and flight delay predictions.

B) DATA-DRIVEN AIR TRAFFIC MANAGEMENT

The availability of new data technology, such as Automatic Dependent Surveillance Broadcast (ADS-B), allows for real-time aircraft position broadcast, fundamentally changing the existing ground-based surveillance system. Given the positional accuracy and updated rates of system errors, this transition enables a host of technological advancements, such as Airborne Separation Assurance, where pilots manage safe separation with other aircraft and get to choose a mission optimal route.

This publicly available aircraft airborne and ground movement data open perspectives to produce new advanced analyses of complex behaviours and collaborative decision-making tools for the optimisation of airport operations.

Such data-driven approaches will allow cost-efficient implementations, which are the key enablers for an efficient integration of small and medium sized airports into the air transportation network. However, for decision-making problems like air traffic conflict resolution, the large and continuous state and action spaces make machine learning methods a challenge.

Since the recent combination of deep learning and reinforcement learning, i.e., deep reinforcement learning (DRL), there is an increased potential of automation for many decision-making problems that were previously intractable because of their high-dimensional state and action spaces.

Deep learning models, like long short-term memory (LSTM) have recently demonstrated high capability of air traffic delay prediction tasks. Deep learning techniques have also been employed to build automated systems in air traffic control.
MARKET AND TECHNOLOGY TRENDS

Air transportation is a highly complex, multi-dimensional, highly distributed and interdependent system. Traditional methodologies are ineffective or infeasible in addressing complex problems in this domain.

Continued traffic growth has been an opportunity but also a challenge to the whole air traffic management ecosystem. It demands increasingly higher workload from controllers, which is limited not only by the capacity of the controllers but also by the capacity of the ecosystem to train and produce more controllers to cope with the growth. Moreover, the capacity to introduce more airspace sectors is also severely challenged, as the sectors are already too small to be divided further, either horizontally or vertically.

A) AUTOMATION AND HUMANS

Automation has been the target of the air traffic management research community for more than 40 years. However, air traffic controllers, for the simple reason that the proposed solutions were not suitable for their human decision-making habits, have not accepted as many advances. Most of the approaches were based on rule-based and optimisation techniques, which posed conflict resolution as an objective function to optimise, subject to constraints such as minimum separation standards with other aircraft in the environment. Based on AI, some dynamic approaches have proposed powerful solutions to complex conflict clusters involving a large number of aircraft, but none are considered as transparent to air traffic controllers, nor adapted to their decision-making strategies.

B) HUMAN COGNITIVE LIMITS

Another key challenge in air traffic is to perform higher-order cognitive tasks such as conflict detection. This task requires the air traffic control officer (ATCO) to maintain situational awareness of current and future air traffic condition to ensure a safe and efficient flow of every aircraft in a shared airspace. Much research and development works have been performed to develop assistance tools for ATCOs to reduce their workload whilst improving their performance. The pioneering researchers relied on mathematical models of aircraft, conflict scenarios, and airspace structure to compute conflict resolution strategy. These mathematical models can hardly scale up for huge numbers of aircraft and might fail to describe the complete dynamics of air traffic. Moreover, these automated tools were not fully trusted as most models behave like a black box to ATCOs.

Besides, the conflict resolution advisories might be very different from ATCOs’ expectations, resulting in their low acceptance rate. Hence, ATCOs have to remain in active control of the air traffic management.

C) WHEN MATHS IS NOT ENOUGH

While mathematical models showed their limitation in incorporating human preferences or strategies in their solution, AI (e.g., deep learning and reinforcement learning (RL)) has achieved superhuman level in a variety of strategical tasks (e.g., diagnosing a number of cancers and playing the games of Go and Atari). Recently, behaviour cloning and inverse RL have demonstrated machine abilities in mimicking the experts’ behaviours from the demonstrations or even infer the reward function of human strategies. Following this line of research, RL can be adopted in air traffic control task to learn how ATCOs perform conflict resolutions.
5. RESEARCH AND DEVELOPMENT AT THE COLLEGE OF ENGINEERING

College of Engineering (CoE), NTU, is a world leader in the research areas of Air Traffic Management (ATM) and Artificial Intelligence (AI). To tackle the challenges brought on by the rapid increase in air traffic, CoE is actively engaged in developing innovative technologies in AI to create smart solutions for ATM systems.

In the near future, CoE envisions a hybrid AI-Human ATM system, with the aim to create intelligent, interactive and trusted ATM systems for effective collaboration between humans and machines; a paradigm shift in this industry. In this vision of the future, machines will be able to learn safety-critical tasks from humans, and evolve into reliable AI-based assistants for human controllers.

CoE has also initiated research into mutual trust between the human controllers and the machine learning systems, a crucial component in the hybrid AI-Human ATM systems of the future.

CoE has developed several solutions in the space of Intelligent Agents for ATM, especially in terms of airspace capacity prediction, airway network optimisation, and identification of unstable configurations in terminal airspace. These solutions, coupled with machine learning techniques to predict hotspots, taxi-time, flight arrivals and delay, would immensely enhance the efficiency of future Air Traffic Management (ATM) operations.

5.1 THE AI-HUMAN HYBRID ATC SYSTEM

The hybrid AI-Human ATM system will be driven by cognition (neuro-psycho-physiological) and operational (airspace, weather, aircraft, air traffic and airport) data. There is also the need to define the architecture of the complex future systems involving multiple AI-based agents for distributed decision making between ATCOs. This mode of federated and collaborative learning, preferably privacy-preserving in practice, would be essential for traffic management across various functional blocks of an airspace, defining a completely new future role for air traffic controllers. CoE’s research in creating hybrid AI-Human ATM systems is now recognised globally.
A) MACHINE LEARNS SAFETY CRITICAL TASKS FROM HUMAN

The increasing technological trend of "personalised automation", where automated decision supports are customised to each controller, exploits the powers of state-of-the-art machine learning techniques, in particular, unsupervised learning. Results obtained from initial investigations at ATMRI have demonstrated that by designing AI-based assistants that can learn from human controllers and can propose solutions that converge with human decision-making habits, trust between controllers and their respective AI assistants could increase. Therefore, under high traffic demands, controllers would possibly delegate some major tasks to AI assistants, and by doing so, would be able to handle more traffic. This will eventually elevate an air traffic controller to the role of an air traffic manager. The ultimate objective of ATMRI is to design and develop hybrid AI-Human ATC systems where AI assistants and human ATMs could work collaboratively under high workloads.

Figure 8: The hybrid AI-Human ATM system for air traffic conflict resolution [18]

B) HUMAN AND MACHINE LEARNING TO TRUST EACH OTHER

With a greater proliferation of automation tools in the domain of ATM due to exponential growth in air traffic, human factors, and more specifically, trust, becomes a crucial component of ATCO automation teams. CoE has attempted to better represent trust behaviours in ATCOs by juxtaposing two philosophies of trust using the principles of superposition and complementarity from quantum mechanics.

Neuroimaging evidence of this simultaneous concurrence are demonstrated with the use of functional magnetic resonance imaging (fMRI) data. The robustness in this proposed model is higher due to the use of objective data to explain ATCO's trusting behaviour under uncertainty. This is an improvement on current models that are context-dependent and based on subjective data.

Figure 9: Air traffic controller under MRI scanner identifying air traffic conflicts through an automation aid [19]
5.2 INTELLIGENT AGENTS FOR AIRSPACE OPTIMISATION

Air traffic has long been artificially concentrated on airways with intermediate waypoints, i.e., airway networks, which could result in congestion. Present airway networks have evolved, over a period, without any scientific basis. As new waypoints and airways are added to airway networks to accommodate the increasing traffic in an as-needed manner, the structures of airway networks are becoming more and more complicated. Such networks may also lead to increased workload for air traffic controllers. Moreover, the ever-increasing demand for air travel is likely to induce air traffic congestion which will elicit great economic losses. This research designs intelligent agents and algorithms that optimise the airspace to realise its full potential.

A) AIRSPACE CAPACITY PREDICTION

The growing demand for air travel may induce en-route airspace capacity overload which endangers flight safety and elicit air traffic congestion. The knowledge of airspace capacity overload is important for air traffic flow management and flight planning to mitigate air traffic congestion without compromising airspace safety level. Since the primary task of air traffic controllers is to manage traffic flow within the constraints imposed by safety requirements, i.e., to maintain a low risk of collision, this research employs the aircraft mid-air collision risk for a given airspace as the indicator of airspace capacity overload. With the given air traffic data and airspace configurations, the collision risk distributions inside an airspace is determined through collision risk modelling. Based on the density and intensity of collision risk, the collision risk distributions are converted into heatmaps and collision risk patterns are further recognised from the heatmaps using image processing techniques.

Figure 10: Singapore airspace with complex network of airways [20]

This research explores whether Braess’s paradox occurs in airway networks, or more specifically, whether it is possible to better distribute the flow in an airway network by merely removing some of its airways/links.

This research develops a method using Braess’ paradox detection in any given airway network. To validate the efficacy of the method, a case study is conducted for the Southeast Asia airspace covering Singapore airway network, by using six months of ADS-B data. The results show that Braess paradox does occur in airway networks and the proposed method can successfully identify the airway network links that may cause it. Upon removing such links, total travelling time in the airspace can be improved by 3.8%.

B) AIRSPACE AIRWAY NETWORK OPTIMISATION

In the presence of limited airspace capacity as well as the saturated airway network, it is no longer practicable to mitigate air traffic congestion by adding new airways/links.

This research aims to investigate the possibility of making minimal changes to the structure of an existing airway network to reduce flight durations, thereby alleviating air traffic congestion. More precisely, can we achieve this instead by removing some of the airways (i.e., network links) in an air traffic network? The answer may be yes for some networks. This research draws inspiration from Braess’s paradox which suggests that adding extra links to a congested traffic network could make the traffic more congested.

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Figure 11: Critical nodes and links in Singapore airspace network [17]
C) IDENTIFICATION OF UNSTABLE APPROACH IN TERMINAL AIRSPACE

Air navigation service providers (ANSP) worldwide are striving to exceed the desired safety levels. The terminal maneuvering area (TMA) is one of the most safety-critical areas in ATM as it encompasses the most critical phase of flight, i.e., departure and landing. An aircraft, during the final approach phase, is required to remain in a stable configuration and prevent any undesired state such as an unstable approach, which may subsequently lead to incidents/accidents such as go-around and runway excursions.

This research proposes a data-driven framework to model the aircraft 4D trajectories in the final approach phase by adopting sparse variational Gaussian process (SVGP) model. The model is trained to learn the aircraft landing dynamics from advanced surface movement guidance and control system (A-SMGCS) data, during the final approach phase.

We experimentally demonstrate that SVGP provides an interpretable probabilistic bound of aircraft parameters that can quantify deviation and perform real-time anomaly detection. The findings of this work can increase situational awareness of the air traffic controller and has implications for the design of a new approach procedure in complex runway configurations such as the parallel approach.

Figure 12: Framework for real-time detection of unstable approaches based on A-SMGCS data [21]
5.3 MACHINE-LEARNED AIRPORT OPERATIONS

A) HOTSPOT PREDICTIONS

Airports across the world are expanding by building multiple ground control towers and resorting to complex taxiway and runway systems, in response to growing air traffic. Current outcome-based ground safety management at the airside may impede our potential to learn from and adapt to evolving air traffic scenarios, owing to the sparsity of accidents when compared with number of daily airside operations.

To augment airside ground safety at Changi Airport, this research predicts dynamic hotspots where multiple aircraft may come in close vicinity on taxiways, as precursor events to airside conflicts. Airside infrastructure and ground movement radar data of Changi Airport is used to model aircraft arrival at different taxiway intersections, both in temporal and spatial dimensions.

The statistically learnt spatial-temporal model is then used to compute conflict probability at identified intersections, in order to evaluate conflict coefficients or severity of hot spots. These hot spots are then visually displayed on the aerodrome diagram for heightened attention of ground ATCOs. These hotspots lead to a better understanding of taxiway movements and increased situational awareness.

Figure 13: Machine-learned hotspots at Changi Airport taxiways [22]

B) DATA DRIVEN TAXI-TIME PREDICTION

The ground movement of an aircraft is one of the most critical daily airside operations at any airport. The ground movement problem includes two sub-problems: routing and scheduling, which serve the purpose of guiding aircraft on the surface of an airport to meet the departure schedule while minimising the overall travel time. Ground movement controllers manage the taxi-route assignments and taxi-time estimation for each aircraft in arrival or departure queue.

A high-accuracy taxi-time calculation is required to increase the efficiency of airport operations. This research uses a data-driven approach to construct features set and build predictive models for taxi-time prediction of departure flights. The proposed approach can suggest both taxi-route and predict the corresponding taxi-time by analysing ground movement data.

The controller’s operational preferences are extracted and learned by machine learning algorithms for predicting taxi-route and taxi-time of a given aircraft. In this research, we take advantage of taxiing trajectories to learn the controller’s decision, which reflects how the controller had decided the routing for a given situation.

Two machine learning models, random forest regression and linear regression, are implemented and they show similar performances in estimating the taxi-time. However, our observations have shown that the random forest model can provide a more stable result and interpretability which is suitable for real-world operations. The predictive model for taxi-time can predict the taxi-out time with high accuracy with given assigned taxi-route.

Figure 14: Data-driven prediction of taxi timings at Changi Airport taxiways modelled as nodes on a graph [23]
5.4 DATA-DRIVEN PERFORMANCE METRICS

A) PREDICTION OF FLIGHTS’ ARRIVAL TIME

An accurate prediction of aircraft arrival times is the key component to (i) an optimal flight sequencing to the runway, (ii) an accurate prediction of flight delays, and (iii) a good coordination of ground handling personnel and equipment. Several processes, such as air traffic flow management, airport runway configuration, and mitigating flight delays, rely on accurate aircraft arrival times to be performed optimally. This research uses a data-driven approach that predicts, at the entry fix of a STAR route which is the actual landing time (ALDT) of an aircraft.

Our case of study is the TMA traffic around Changi Airport (WSSS). The TMA trajectory clustering adopts a hierarchical clustering method, after which three prediction models based on the random forest algorithm are proposed. The results show ALDT prediction with a root-mean-square error (RMSE) of two minutes and a mean absolute error (MAE) of five seconds. This approach demonstrates the importance of understanding the shape of TMA trajectory in order to accurately predict arrival time.

B) MACHINE-LEARNED DELAY PREDICTION

Air traffic is confronted with intractable delays due to the imbalance between the rising air traffic demand and the limited airspace capacity. As air traffic is associated with the complex air transport systems, its delays therefore can be magnified and propagated throughout the system, resulting in the emergent behaviour known as delay propagation. Understanding the delay propagation dynamics is pertinent to modern air traffic management. This research takes a complex network perspective towards the delay propagation dynamics.

Specifically, it models the air traffic scenario using spatial-temporal networks with the nodes being the airports. In order to establish the dynamical edges between the nodes, we develop a delay propagation method and apply it to a given set of air traffic schedules. Based on the constructed spatial-temporal networks, we suggest three metrics — magnitude, severity, and speed — to gauge the delay propagation dynamics.

To validate the effectiveness of the proposed method, we carry out case studies on the domestic flights in the Southeast Asia Region (SAR) and the United States of America (USA). Experiments demonstrate that the propagation magnitude in terms of the number of flights that witness delay propagation, and the amount of propagated delays for the USA traffic are five and ten times that of the SAR, respectively.

Experiments further discover that the propagation speed for the USA traffic is eight times faster than that of the SAR. The delay propagation dynamics reveal that about six hub airports in the SAR witness significant propagated delays while the situation in the USA turns grimmer as the corresponding number is around 16. This work provides a potent instrument for tracing the evolution of air traffic delays.
CoE at NTU Singapore has established Air Traffic Management Research Institute (ATMRI), a state-of-the-art research infrastructure in air traffic management and airport operations. This infrastructure is not only used in research and development but also to support ASEAN member states in regional airspace modernisation.

At ATMRI, CoE has set up ATC tower simulators and radar simulators for end-to-end human-in-the-loop simulation of complex air-traffic scenarios and advanced ATM concepts evaluation. ATMRI facilities include a 13-metre wide aerodrome control tower simulator to model the working environments of the Changi Airport control tower cabin, including a 360-degree view of the aerodrome.

The five-position radar simulator, which is geared towards simulating the air traffic control environments of Singapore, is linked to the tower simulator to conduct gate-to-gate simulation and exercises. It can simulate different tower locations and heights, as well as different weather scenarios (visual flight rules and instrument flight rules).
In the radar simulator, there are five controller working positions (CWPs), expandable to seven if needed, and up to 10 pseudo pilot positions, with the capability to operate in area control or approach control mode, as well as in combined mode. An integrated radio/telephony system allows the controller to contact pilots, other controllers or neighbouring sectors or centres. The hardware is driven by specialised software such as NARSIM and AirTop, two of the state-of-the-art simulation tools for airfield performance assessment and for airport resource utilisation optimisation.

In terms of research expertise, the artificial intelligence and data analytics (AIDA) research program at ATMRI comprises of 13 researchers, including four PhD scholars, specialising in machine learning, pattern recognition, image processing, voice analytics and human-machine interactions applied to ATM challenges. The research group made headlines when two of its research papers won Best Paper Awards in prestigious ATM conferences organised by the United States Federal Aviation Administration and EUROCONTROL in 2018 and 2019, respectively.

In 2018 and 2019, the research group has published over 22 peer-reviewed research papers on using AI for solving air transportation problems in high impact journals and international conferences. This line of research at ATMRI is highly recognised by AI communities within the IEEE Computational Intelligence Society (CIS), which sponsored the first International Conference on Artificial Intelligence and Data Analytics in Air Transportation 2020 organised by ATMRI/MAE.

Thus far, ATMRI has hosted several eminent scientists and visiting professors from MIT, University of California (UC), Berkeley, NASA Ames, TU Dresden, TU Delft and ENAC France, facilitating research collaborations and exchanges.
SECTION SEVEN:

OPPORTUNITIES FOR COLLABORATION

Our collaborations take on an array of different forms, ranging from student exchange and teaching partnerships to joint research on global issues. Through our extensive network of international partnerships, we offer opportunities for collaboration on many levels including supporting universities, governments and companies in the development of their staff and providing international experiences for students and staff. Our academic staff collaborate with researchers from around the world to address wide-ranging issues related to air transportation.

To do so, we have a dedicated research team of proactive bright minds and technical experts who actively engage with academic institutions, research bodies, think tanks and other organisations to share our latest ideas for research topics, projects and results. This ensures convergence of initiatives, alignment with the needs of air navigation service provider (ANSP) while creating opportunities for joint initiatives to maximise resource efficiency and minimise duplicating research.
MEETINGS AND WORKSHOPS

We hold one international conference every two years. In addition to this regular meeting, two workshops are organised annually on specific topics selected for their potential impact on ATM research.

Participation in our workshops is open. We invite all researchers who are interested and knowledgeable in the subject matter for discussion.

Please contact Associate Professor Sameer Alam, Deputy Director, Air Traffic Management Research Institute at sameerlam@ntu.edu.sg for further information.
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