Canada's Research Capacity in UAS

A Research Paper commissioned for Transport Canada

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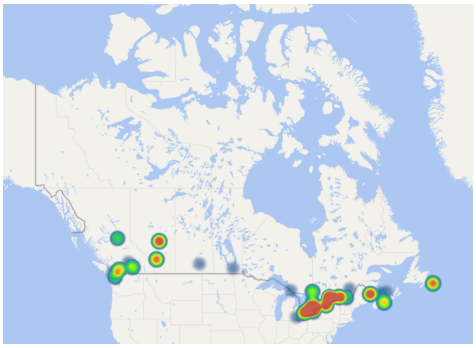
Executive Summary

Unmanned aerial systems (UAS) hold great promise for applications as diverse as natural resource monitoring, infrastructure inspection (pipeline, railways), agriculture, mineral exploration, journalism, and search & rescue operations. This is the most vibrant sector of the aerospace industry, growing more quickly than any other segment. It is forecast that the UAS sector will continue to experience strong growth for the next decade. Given Canada's vast geographical landscape (e.g. the Arctic) and natural resources, the Canadian commercial or civil UAS market is expected to grow rapidly. Canada has a long and successful history of leadership in aviation. Canadian companies and research institutions have also emerged to take leading roles in the growing civilian UAS research and development, nationally and internationally. A research paper is commissioned for Transport Canada's Innovation Policy Directorate to provide an overview of Canada's research capacities in UAS, especially to cover the landscape of Canadas academic networks, and research institutions in this area.

The key findings of the research paper are highlighted here:

- 127 researchers, 6 multi-institutional, multi-disciplinary research centres are identified across Canada
- Canada's research capacity in UAS development is charted by 5 major disciplines: aerodynamics (AER), guidance, navigation and control (GNC), design and manufacturing (ADM), propulsion (PRP), and structures and materials (SM). The research focus is placed on GNC (68%), the research direction points to the integration of UAS, and intelligence of UAS development.
- Canada's research capacity in UAS development is charted by 9 commercial and civil application domains, including infrastructure, environment, natural resources, agriculture, public safety, delivery, arts and defence (military). Research and development is consistent with Canada's landscape and resources, over 83% applications cover infrastructure (16%), environment (27%), natural resources (19%), and agriculture (21%)
- Canada's research capacity in UAS development is also charted by regions, where 53% is located in Ontario. The rest are evenly distributed between western (AB, BC, MB, SK 24%) and Quebec and maritime provinces (22%)



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1 Introduction

Unmanned Aerial Systems (UAS) hold great promise for applications as diverse as natural resource monitoring, infrastructure inspection (pipeline, railways), agriculture, mineral exploration, journalism, and search & rescue operations. This is the most vibrant sector of the aerospace industry, growing more quickly than any other segment. It is forecast that the UAS sector will continue to experience strong growth for the next decade, and UAS technology is positioned to become disruptive to many different application areas. While the majority of the UAS market has historically been dedicated to military and security applications, the bulk of the predicted growth will come from civilian applications. Given Canada's vast geographical landscape (e.g. the Arctic) and natural resources, the Canadian commercial or civil UAS market is expected to grow rapidly. Canada has a long and successful history of leadership in aviation. Canadian companies and research institutions have actively participated in the growing civilian and commercial UAS research and development, even take leading roles in some areas, nationally and internationally.

It is strategically important to have a good understanding of where we are in this emerging sector in terms of interdisciplinary research, entrepreneurship, and leadership. A research report is commissioned for Transport Canada's Innovation Policy Directorate to provide an overview of Canada's research capacities in the UAS, especially to cover the landscape of Canada's academic networks, research institutions in this area. In other words, the focus of this report is placed upon the research 'roadmap' within Canada's landscape. A long-term, more ambitious goal of such a study exercise is to identify strategic themes in UAS research and development that are vital to build strong capabilities in selected areas with international reputation. It will also offer some guidelines to discover and create opportunities in the UAS sector that will propel Canadian aerospace companies and research community forward into a prosperous future in this field. It may encourage Canadian researchers to bring their unique expertise and collectively span all key scientific and technological areas related to the research and development of versatile UAS platforms for civil applications. With these viewpoints, the commissioned research paper will address the following key points:

- UAS research and development categorized by regions, research areas, and development applications
- A list of Canada's major academic units, and research institutions that have a dedicated UAS portfolio
- Preliminary data analysis based on the roadmap.

2 Scope of Study

The scope of study covers the following search and surveys:

- a comprehensive search of UAS related research was conducted through the website of the Natural Science and Engineering Research Council (NSERC) of Canada (2013-17)[1], where research grant competition results are available to public;
- a comprehensive search of UAS related research was conducted through ALL universities across Canada, based on the "Universities Canada"[2] membership list;
- ad hoc web search by subjects, plus personal knowledge in the field.

Based on the above scope of search, the rest of the report is divided into four sections. Section 3 covers Canada's research capacity in the category of UAS development disciplines, where the subjects are classified by traditional aeronautical science and engineering disciplines, including aerodynamics, guidance, navigation and control (GNC), aircraft design and manufacturing, propulsion, structures and materials. Section 4 presents Canada's research capacity in the category of UAS application areas, including infrastructure, environment, agriculture, public safety, natural resources, delivery, arts, as well as defence (military). Section 5 describes Canada's research capacity categorized by the geographical landscape. Section 6 makes a list of major academic units, research institutions that have a dedicated UAS portfolio.

2.1 Author's Disclaimer

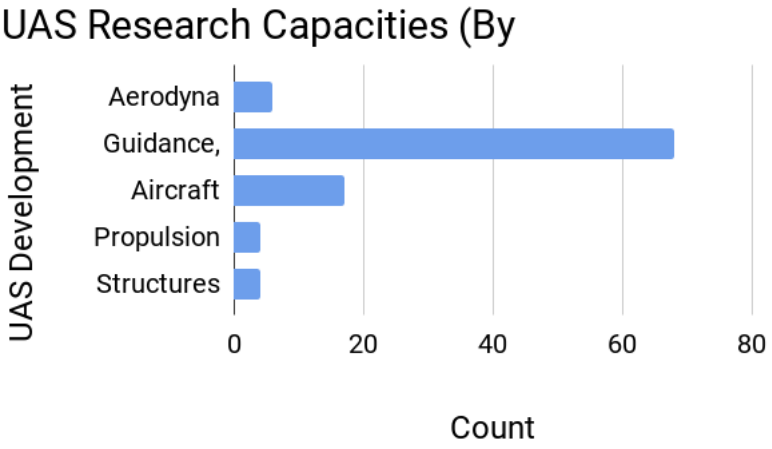
Since the author himself is an academic with the University of Toronto, the report has a bias weight reporting on the province of Ontario, due to his personal knowledge. He currently also serves as the Director, University of Toronto's Centre for Aerial Robotics Research and Education (CARRE), which is included in the document.

[1] `http://www.nserc.ca`
[2] `http://www.univcan.ca`

3 Research Capacity by UAS Development Disciplines

Canada's research capacity in the category of UAS development disciplines, where the subjects are classified by traditional aeronautical science and engineering disciplines

- aerodynamics (AER),
- guidance, navigation and control (GNC),
- aircraft design and manufacturing (ADM),
- propulsion (PRP), and
- structures and materials (SM)



These research and development areas are selected for two reasons: 1) they cover technology disciplines that are standard in aerospace science and engineering, and are compatible with traditional aircraft technologies, easy for comparative study; 2) these technical areas are considered directly contributed to UAS development. It helps to distinguish from R&D related areas that are user-based, application oriented. The latter scenario will be covered in the next section. Based on the scope of search, 128 researchers are identified to have UAS portfolio, where 99 researchers are involved in the UAS development categories.

6 out of 99 researchers are identified in 'aerodynamics'. The UAS aerodynamics research and projects include: Aerodynamic characterization and improvement of an unmanned helicopter (Ghaemi); Multidisciplinary Design Optimization (Suleman); Whirl-tower Open Loop Experiments and Simulations with an Adaptive Pitch Link Device for Helicopter Rotor Vibration (Nitzsche); Climatic Wind Tunnel, Hemi-Anechoic Chambers, shaker table, UAV Testing Ground, UAV Proving Ground (Ekmekci); Drones for enabling computational environmental flow dynamics studies (Bitsuamik).

4 out of 99 researchers are identified in 'propulsion'. The UAS propulsion research and projects include: Multidisciplinary design optimization of UAVs (Suleman); Hybrid Power Plant Design (Gueaicb); Dynamic Characterization of Brushless DC Motors and Propellers (Lanteigne); Fuel cell power systems for UAV applications, Lightweight High-Performance Fuel Cells for Unmanned Aerial Vehicle Propulsion (Zhou).

4 out of 99 researchers are identified in 'structures and materials'. The UAS structures and materials research and projects include: Composite Materials (Mertiny); Multidisciplinary design optimization of UAVs (Suleman); Printed unmanned aerial vehicles using paper-based electroac-

tive polymer actuators and organic ion gel transistors (Grau).

Quite a few (17 out of 99) researchers are identified in 'aircraft design and manufacturing'. The UAS design and manufacturing research and projects include: Scalable Highly Maneuverable Unmanned Aerial Vehicles for Confined Spaces (Ramirez-Serrano); Multidisciplinary design optimization of UAVs (Suleman); PrecisionHawk conducted to improve the state of the art in UAV systems, remote sensing and airspace safety (Furgeson); Marine Robot Autonomy, Developement of Autonomous Vehicles (Sato); Design and Manufacturing of Biologically Inspired Micro Aerial Vehicle Wings Using Rapid Prototyping (Laliberte); Design of a Novel Auto-Rotating UAV Platform for Underground Mine Cavity Surveying (Marshall); Design, Construction and Testing of a Novel UAV Platform for Cavity Surveying (Mitchell); BitDrones: Towards Using 3D Nanocopter Displays as Interactive Self-Levitating Programmable Matter (Vertegaal); Design and testing of foam-inflated wings for small unmanned aerial vehicles, study of Micro Aerial Vehicles in Confined Spaces (Bramesfeld); Omnicopter, Disturbance Rejection (Nokleby); Long-range Communication Framework for Autonomous UAVs, Design and Control of a Quadrotor Unmanned Aerial Vehicle, UAV Based System for Real Time Flash Flood Monitoring in Desert Environments Using Lagrangian Microsensors, Hybrid Power Plant Design (Gueaieb); Hybrid power plant, energy efficient path planning, trajectory optimization, pitch control of tilting bi-rotor, Dynamic Characterization of Brushless DC Motors and Propellers, Height Estimation of a Blimp Unmanned Aerial Vehicle Using Inertial Measurement Unit and Infrared Camera (Lanteigne); Synchronized Swarm of Unmanned Vehicle Systems for Large-Scale Dynamic Applications, Forest Fire Monitoring, VTOL fixed-wing AV, Formation Control, Autonomous Soaring SUrveillance, Visual-based surveillance and sensing using multi-UAVs, Fault-Tolerant Control (Liu); Printed unmanned aerial vehicles using paper-based electroactive polymer actuators and organic ion gel transistors (Grau); Aircraft Modeling and Simulation (Botez); UAV for water survalliance (Pomeroy).

Majority of researchers are identified in the development category of 'guidance, navigation and control', which is not surprising. GNC has played a critical role of providing enabling technology in the UAS research and development. Instead of covering every single research topic, projects are divided into the following subjects:

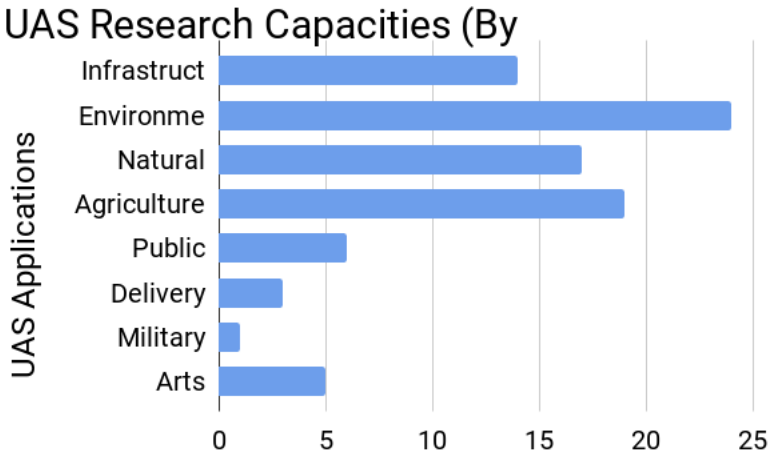
- vision-based (enhanced) research to enable/improve autonomy (Barczyk, Barfoot, Kelly, Dudek)
- UAS in unstructured (uncertain, confined, GPS denied) environment (Lynch, Ramirez-Serrano, Bramesfeld, Mehrandezh)
- UAS Navigation (Barczyk, Furgeson, Li, Atia, El-Rabbany, Nokleby, McCabe, Waslander)
- path planning (Sasiadek, Lanteigne, Liu)
- collision/obstable avoidance (de Ruiter, Liu, Desbiens)
- UAS performance (Vaughan)
- localization and mapping (Najjaran, Kelly, Polushin, Jenkin)
- flight control (Shi, Liu, Zhang, Mann, Etele, LiuX, Givigi, LiuG, Schoellig, Maggiore, Mills,

Berkane, Roberts, Nahon, Sharf, Ny, Paranjape)
- sensing (Al-Tahir, Coleman, De Silva, Gong, Straznicky, Glen, Armenakis, Mackenzie, Remmel)
- coordination, formation, cooperation (Liu, Mann, Pan, Tayebi, Kirubarajan, Cheng, Shen, Abdessameud)
- operations (O'Young)
- intelligent algorithms (including NN, AI) (Liu, Schwartz, Ouyang, Necsulescu, Meger, Eramian)
- Simulation, Virtual Reality, Augmented Reality, (Chung, Botez, Peter Grant)
- communicaitons (Gueaieb)

4 Research Capacity by UAS Applications

Canada's research capacity in the category of UAS applications, where the subjects are classified by potential commercial applications.

- infrastructure
- environment
- natural resources
- agriculture
- public safety
- delivery
- defence (military)? and
- arts



Infrastructure applications include but not limited to: pipeline inspection, power line inspection, construction, mapping. Some projects are:

- innovative mapping applications (Wang, Najjaran)
- remote sensing (Fisher, McLeod, Armenakis, Zhang, Théau)
- terrestrial photogrammetry (Tannant, Ferworn)
- special (inaccessible, indoor) infrastructure (Hildebrand, McCabe)

Environment applications include but not limited to: Disaster Monitoring, Forestry, Hydrology, Wildfire, Wetland Inspection, Environment Monitoring. Geography, geology are also categorized here. Some project topics include:

- image and video analysis (Ray, Robichaud)
- intelligent algorithms (include DL, AI) (Ray, Meger, Théau)
- mapping, survey (McDermid, Shahbazi, Hill, Shaw, Shea, Jenkin)
- remote sensing (Eaton, Daggupati, Armenakis, Pomeroy)

- precision applications (Leblon)
- modeling, database (Kovacs, Aaron)
- GNC (Liu, Zhang, Schoellig)

Natural resources applications include but not limited to: mining, wildlife. (McDermid, Shahbazi, Wang, Reich, Coops, Hunt, Najjaran, Runesson, Dech, Braun, Hassanein, Marshall, Mitchell, Franklin, Schoellig, Théau

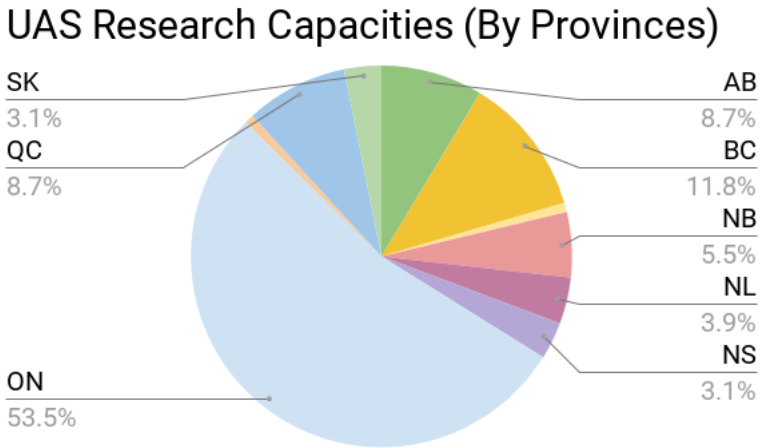
Public Safety applications include but not limited to: search and rescue, surveillance (Najjaran (Liu, Armenakis, Jain, Mehrandezh, Paranjape).

Agriculture applications include but not limited to: farming. Examples include: vineyard (Jamieson), cattle (Church), precision agriculture (Leblon, Walters), soil moisture/nutrient (Aaron), vegetation (He).

Arts applications loosely assemble the following: media, culture, entertainment, journalism.

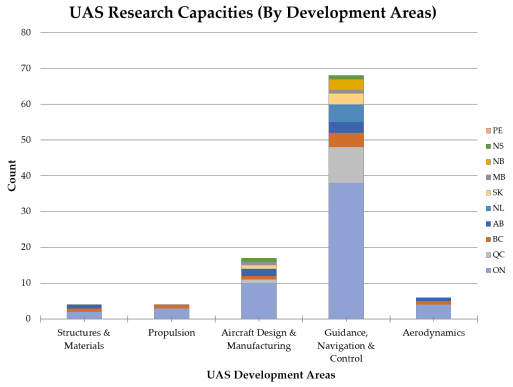
5 Research Capacity by Regions

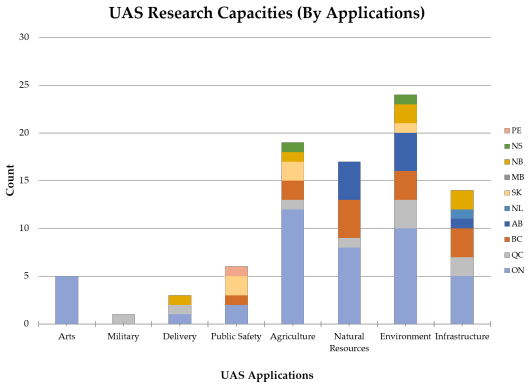
Canada's research capacity in the category of regions, specifically by provinces, are self explanatory.



The distribution may not be accurate or even fair, for a couple of factors. 1) it has a bias weight reporting on the province of Ontario, due to the author's personal knowledge; 2) the researchers in Quebec are much smaller than expected, partially due to language barriers during the scope of search.

The regional distribution can further be broken down into their respective development disciplines and applications.





6 UAS Research Centres and Specialist Groups

Based on the scope of search, a number of UAS research centres, specialist groups are identified with dedicated UAS profile. The following list is organized alphabetically.

CARRE `http://carre.utoronto.ca/` The University of Toronto's Centre for Aerial Robotics Research and Education (CARRE) was established in May 2015 to meet the demand for engineers and scientists with the highly interdisciplinary training needed to contribute to the burgeoning field of Unmanned Aerial Systems (UAS) and aerial robotics. The objective of CARRE is to become an internationally-recognized centre for aerial robotics and the nucleus of aerial robotics research and teaching at the University of Toronto. The development of commercial UAVs requires a broad array of technical skills, across multiple disciplines - CARRE brings together aerodynamicists, structural designers, materials engineers, propulsion experts, control specialists, and roboticists, to design and develop state-of-the-art aerial robotic platforms. CARRE is able to leverage the range of expertise available at UTIAS, partner institutions, and industrial collaborators.

UVic CfAR `http://www.uvic-cfar.com/index.html` The UVic Center for Aerospace Research is an organization devoted to the promotion of Unmanned Aerial Vehicles for commercial and research applications. UVic CfAR is available to partner with industry in order to apply research in the area of unmanned aircraft to real world applications. UVic CfAR develops application specific solutions using our wide range of capabilities and industrial partners. This includes design, ground and flight based testing or manufacture.

The **ACE Centre for UAV Research**, located at the University of Ontario Institute of Science and Technology `http://ace.uoit.ca/uav/index.php` utilizes the most sophisticated climatic

wind tunnel and testing chambers in the world to push the UAV industry into new territories. At this epicenter of UAV research and product development, [the centre] helps researchers and manufacturers discover what it takes to handle the harshest climates on earth from frigid northern storms to the hottest desert heat.

Centre for Innovation and Research in Unmanned Systems. http://www.sait.ca/ Southern Alberta Institute of Technology (SAIT) is supporting innovation and new technology development through its Centre for Innovation and Research in Unmanned Systems (CIRUS). Researchers with SAIT's Applied Research and Innovation Services department, faculty from SAIT's School of Construction, students and industry partners converge in this cross-disciplinary environment to address challenges, create efficiencies, and develop and test new products and applications. CIRUS will expand the role unmanned systems play in data acquisition and management, and create organizational efficiencies across a variety of sectors and regulatory environments.

The **Canadian Centre for Unmanned Vehicle Systems** (CCUVS) http://www.ccuvs.com/ is a federally registered not for profit company (2007), located in Medicine Hat, AB whose purpose is to facilitate sustained, profitable growth in the Canadian civil and commercial unmanned systems sector. CCUVS is governed by a Board of Directors, drawn from across Canada, representing academia, industry and government and working primarily in the air unmanned systems environments. Head office staff members are based in Medicine Hat, Alberta.

National Research Council Canada's **Civilian Unmanned Aircraft Systems program**. https://www.nrc-cnrc.gc.ca/eng/index.html Unmanned aviation systems have the potential to accomplish tasks faster, safer and more reliably than their manned equivalents. The Civilian Unmanned Aircraft Systems (CivUAS) program proactively aims to develop, advance, de-risk and certify innovative UAS solutions for key industrial sectors in Canada. With a proven ability to partner with industry on research and technology development across multiple disciplines, the CivUAS program plays an important role in supporting the emergence of unmanned flight into the commercial aviation sector. The program further offers an unmatched technology infrastructure and complementary technical expertise that will foster the integration of UAS technology into key sectors such as oil and gas, defence and security, agriculture, natural resources and critical infrastructure environment.

It is worth pointing out the following organizations and societies that are affiliated with UAS research and development in Canada.

- **Unmanned Systems Canada** https://www.unmannedsystems.ca/about-us/ Mission statements: "to represent the interests of the unmanned vehicle systems community which includes industry, academia, government, military, and other interested persons; to promote public awareness, education and appreciation for the Canadian unmanned vehicle systems community to itself, to Canadians and worldwide."

- **Canadian Aeronautics and Space Institute** `http://www.casi.ca/` Vision and Mission: "to advance the art, science, engineering and applications relating to aeronautics, space and related technologies in Canada; to provide a focus for communications and networking for aeronautics and space communities in Canada; to assist members in developing skills, exchanging information, and sharing talents in their areas of interest; to promote Canadian competence and international competitiveness in aeronautics, space and related technologies and their applications; to foster national pride and international esteem for Canadas accomplishments in aeronautics, space and related technologies."
- **Aerospace Industries Associations of Canada** `http://aiac.ca/` AIAC is the voice of Canadas aerospace industry. The mission is "to understand, build consensus and provide leadership on policy issues of interest to the industry, also work to increase Canadas profile on the world stage by communicating our air and space accomplishments and by promoting Canadian aerospace companies in foreign markets."

7 Industrial Collaboration

During the exercise of mapping Canada's research capacity in UAS development, we did not look into specific data of industrial collaboration by the researchers and research institutions. However, based on my knowledge and experience associated with man of them, I would say the majority of them are actively engaged in collaborative research projects with one or more industrial partners. This aspect may be a topic of interest for future exploration[3]

8 Conclusions

This report presents the landscape of Canada's research capacity in Unmanned Aerial Systems (UAS) development. The coverage is described by three different perspectives: development disciplines, applications, and regions. In terms of disciplines, the roadmap is charted 5 major technical aspects: aerodynamics (AER), guidance, navigation and control (GNC), design and manufacturing (ADM), propulsion (PRP), and structures and materials (SM). The research focus is placed on GNC (68%), the research direction points to the integration of UAS, and intelligence of UAS development. In terms of applications, the roadmap is charted by 9 commercial and civil application domains, including infrastructure, environment, natural resources, agriculture, public safety, delivery, arts and defence (military). Research and development is consistent with Canada's landscape and resources, over 83% applications cover infrastructure (16%), environment (27%), natural resources (19%), and agriculture (21%). In terms of regional distribution, the findings are: 53% located in Ontario. The rest are evenly distributed between western (AB, BC, MB, SK 24%) and Quebec and maritime provinces (22%).

[3]Anecdotal collection of UAS companies is available in the data file.

Acknowledgement

The author would like to acknowledge the students from my research group (Flight Systems and Control Lab, University of Toronto Institute for Aerospace Studies) who helped to search and collect data, especially Yih Tang Yeo, Blago Hristovski, Kelvin Wu, Joshua Furtado, who helped to categorize the data and plot many different charts. Silas Gragham, Han (Flora) Fu, Katharina Krieger, who contributed to the data.

Author's Brief Biology

Hugh H.T. Liu is a Professor of the University of Toronto Institute for Aerospace Studies, where he has been on the faculty since 2000. He currently also serves as the Director of Natural Science and Engineering Research Council of Canada (NSERC) Collaborative Research and Training Experience (CREATE) Program on Unmanned Aerial Vehicles and Centre for Aerial Robotics Research and Education. He received his Bachelors degree from Shanghai Jiao Tong University (1991), Masters degree from Beijing University of Aeronautics and Astronautics (1994), and Ph.D. from the University of Toronto (1998). His research interests in the area of aircraft systems and control include autonomous unmanned systems, cooperative and formation control, fault tolerant control, active control on advanced aircraft systems, as well as integrated modeling and simulations. Prior to his academic appointment, Dr. Liu was a systems engineer at AlliedSignal (now Honeywell) Aerospace Canada where he worked on various aircraft systems projects. He has served many years as a member of the AIAA Guidance, Navigation, and Control Technical Committee. He currently serves as the Associate Editor of AIAA Journal of Guidance, Control and Dynamics. He is also an Associate Editor of the Canadian Aeronautics and Space Journal. Dr. Liu is a fellow of Engineering Institute of Canada, an Associate Fellow of AIAA, a Fellow of Canadian Society of Mechanical Engineers, and a registered Professional Engineer in Ontario, Canada.