A Full-Day Pre-Conference Workshop for 2012 American Control Conference (ACC 2012)

June 26, 2012, Montreal, QC, Canada

Location: Fairmont Queen Elizabeth in Montreal

http://a2c2.org/conferences/acc2012/workshops.php

Advance registration at ACC 2012 Registration Site due: May 1, 2012

Workshop title:

Health Management, Fault-tolerant Control, and Cooperative Control of Unmanned Aircraft

Brief statement of the workshop goals:

Unmanned systems including Unmanned Aerial Vehicles/Systems (UAVs or UAS), Unmanned Ground Vehicles (UGVs), and Unmanned Underwater Vehicles (UUVs) etc are gaining more and more attention during the last a few years due to their important contribution and cost-effective application in several tasks such as surveillance, search, rescue missions, geographic studies, military and security applications. Health management and fault-tolerant control of manned aerial vehicles have a long history since the initial research on self-repairing flight control systems in US Air Force and NASA begun in mid-1980s. However, due to safety of manned aerial vehicles to the pilot, experimental test and further practical research and development have been bounded due to such constraints. Benefited from the recent and significant advance and development of UAVs, development and application of fault-tolerant control as well as cooperative control techniques have been emerged and developed quickly in recent years, since UAVs provide a cheap and operative experimental test-bed for development, implementation, and testing the latest developed fault-tolerant and cooperative guidance, navigation and control techniques. Based on the experiences gained by the 9 different participating organizations ranging from academic institutions, research organization, and industry of the leading groups in Canada, USA, France, and UK, the workshop will demonstrate the state-of-the-art techniques and development in health management, fault diagnosis, fault-tolerant guidance, navigation and control, safety and reliability, as well as multi-vehicle cooperative guidance, navigation and control techniques.

In this workshop, overview of past, current and future research activities and research outcomes on the health management, fault diagnosis, fault-tolerant control, and cooperative control applications with emphasis to UAVs will be presented, which include quadrotor rotary and fixed-wing UAVs etc. Linear and nonlinear techniques for modeling, fault diagnosis, fault-tolerant control, path and trajectory planning/re-planning, cooperative/formation flight guidance, navigation and control, based on a quadrotor helicopter UAV and several fixed-wing UAVs testbeds will be presented in the workshop. Furthermore, health management, fault-tolerant control, and cooperative control strategies development with practical application scenarios on persistent surveillance and coverage control with multiple unmanned systems will be presented. Multiple UAS operations toward verifiable autonomy and assessment of the potential insertion of UAS in the air transportation system will also be discussed.

Audience will gain information and knowledge on the latest development and applications on the active research topics in health management, fault detection and diagnosis, fault-tolerant control and cooperative control of unmanned aerial vehicles from world-leading researchers. Audience will also have opportunity to visit a set of quadrotor helicopter UAVs at the Networked Autonomous Vehicles Lab (NAVL) of Concordia University for real flight demonstrations of fault-tolerant and cooperative control techniques presented in the workshop, in addition to the demonstrations and videos to be shown during the presentation of each presenter.

Presenters:

The workshop consists of 9 presenters from the leading research groups in the relevant fields of the above workshop title in North American [Canada (4) and USA (2)] and Europe [France (1) and UK (2)], where 6 presenters are from academia, 1 presenter is from national research laboratory, and 2 presenters are from industry. Most of presenters have worked on the relevant areas for a long time and made significant contributions in the field, which are evidenced by several first books published in the relevant areas worldwide as can be seen at the end of the proposal, as well as many research publications which can be found from the webpage of each presenter.

Detailed contacting information and brief biography of each presenter are given as follows:

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Brief biographies of presenters:

Youmin Zhang is an Associate Professor in the Department of Mechanical and Industrial Engineering and the Concordia Institute of Aerospace Design and Innovation (CIADI) at Concordia University, Canada. His main research interests and experience are in the areas of condition monitoring, fault diagnosis and fault-tolerant (flight) control systems; cooperative guidance, navigation and control of unmanned aerial/ground vehicles; dynamic systems modeling, estimation, identification and control; and advanced signal processing techniques for diagnosis, prognosis and health management of safety-critical systems and manufacturing processes. He has published 4 books, over 200 journal and conference papers. He is a senior member of AIAA, senior member of IEEE, a member of the IFAC Technical Committee on Fault Detection, Supervision and Safety for Technical Processes, and a member of the AIAA Infotech@Aerospace Program Committee (PC) on Unmanned Systems. He is an Editorial Board Member of several international journals and IPC member of many international conferences.

Camille-Alain Rabbath is a Defense Scientist at Defense Research and Development Canada (DRDC). He also holds adjunct professorship positions at Concordia University and McGill University, Montreal, Canada. His current research interests are in real-time control and distributed modeling and simulations, nonlinear sampled-data control, guidance, and multi-vehicle cooperative decision and control. He is Associate Editor for the journals IEEE Transactions on Control Systems Technology, Transactions of the Canadian Society for Mechanical Engineering, and Control Engineering Practice, and for the IEEE Canadian Review magazine. He is a senior of IEEE, a member of AIAA and OIQ.

YangQuan Chen received the B.S. degree in industrial automation from the University of Science and Technology of Beijing, Beijing, China, in 1985, the M.S. degree in automatic control from the Beijing Institute of Technology, Beijing, in 1989, and the Ph.D. degree in advanced control and instrumentation from the Nanyang Technological University, Singapore, Singapore, in 1998. He is currently an Associate Professor of electrical engineering at Utah State University, Logan, and the Director of the Center for Self-Organizing and Intelligent Systems.

Christopher Edwards is a Professor of Engineering in the Department of Engineering at the University of Leicester. He graduated from Warwick University in 1987 with first class honor in Mathematics and was appointed as a Lecturer in Control Engineering at Leicester in 1996, promoted to Senior Lecturer in 2004, Reader in 2008 and awarded a personal chair in 2010. He has an international reputation for his work on advanced fault-tolerant control, with particular application to aerospace systems. He is the author of over 240 refereed papers, 14 chapter contributions to edited monographs and three books: "Sliding mode control: theory and applications" (1998), "Fault tolerant flight control: a benchmark challenge" (2010), and "Fault detection and fault tolerant control using sliding modes" (2011).

Cameron Fulford received his B.A.Sc. degree with honours in Computer Engineering from the University of Waterloo, Canada, in 2005 and his Masters degree in Electrical Engineering with the Systems Control Group at the University of Toronto, Canada, in 2007. His research studies included nonlinear control and system identification of a 5-DOF magnetically levitated positioning device. He is currently the Engineering Manager of the Systems and Control Group at Quanser Consulting Inc. in Markham, Ontario, Canada. Cameron is the lead engineer for the development of Quanser's Unmanned Vehicle Systems Lab and related technologies. Cameron's interests include the development of educational unmanned vehicle platforms, multi-vehicle control, sensor integration, and the development of rapid controls prototyping hardware and software.

Hugh H.T. Liu is an Associate Professor at the University of Toronto Institute for Aerospace Studies (UTIAS), Toronto, Canada, where he also serves as the Associate Director, Graduate Studies. His research work over the past several years has included a number of aircraft systems and control related areas, and he leads the "Flight Systems and Control" (FSC) Research Laboratory. Dr. Liu is an internationally leading researcher in the area of aircraft systems and control. He has published over 100 technical papers in peer reviewed journals and conference proceedings, and he has received one US/Canada patent of his work on motion synchronization. Dr. Liu has made significant research contributions in autonomous unmanned systems development, cooperative control, and integrated modeling and simulation. He also serves on editorial boards and technical committees of international professional societies. Before his academic appointment, Dr. Liu has several years' industrial experience where he participated and led development projects of aircraft environmental control systems. Dr. Liu received his Ph.D. in mechanical engineering of the University of Toronto in 1998. He is an active member of IEEE, AIAA, CASI, and Fellow of CSME. Dr. Liu is also a registered Professional Engineer in Ontario.

Liang Tang is an Intelligent Control and Prediction Lead at Impact Technologies. Dr. Tang's career has been focused on the development of health management and intelligent control solutions for a wide range of military and commercial systems. His recent work has also involved developing data fusion, tracking and navigation technologies for various unmanned autonomous platforms. He is currently the Principal Investigator of multiple NASA and DoD SBIR/STTR programs developing fault tolerant control strategies for advanced autonomous system, GPS-independent inertial navigation device for UAV and USV, fault diagnostic algorithms for jet engine and distributed data fusion system for USVs. He received his Ph.D. degree from Shanghai Jiao Tong University, China, where his research focused on nonlinear system identification and controls with applications to robotics and power systems. Before he joined Impact Technologies, he was a research fellow with the School of ECE, Georgia Institute of

Technology, where he conducted research on fault diagnosis and controls of UAVs. He has published more than 50 papers in his areas of expertise.

Didier Theilliol received the Ph.D. degree in Control Engineering from Nancy-University (France) in 1993. Since September 2004, he is a full Professor in Research Centre for Automatic Control of Nancy (CRAN) at Nancy-University where he co-ordinates and leads national, European and international R&D projects in steel industries, wastewater treatment plant, or aerospace domain. His current research interests include sensor and actuator model-based fault diagnosis (FDI) method synthesis and active fault-tolerant control (FTC) system design for LTI, LPV, Multi-linear systems and also reliability analysis of components. Prof. Theilliol published over 100 journal/conference papers and is co-author of a new book entitled "Fault-tolerant Control Systems: Design and Practical Applications" (2010).

Antonios Tsourdos is a Professor and Head of the Centre for Autonomous Systems at Cranfield University, Defence Academy of the United Kingdom. He was member of the Team Stellar, the winning team for the UK MoD Grand Challenge (2008) and the IET Innovation Award (Category Team, 2009). Antonios is an editorial board member of the Proceedings of the IMechE Part G Journal of Aerospace Engineering, the International Journal of Systems Science, the IEEE Transactions of Instrumentation and Measurement, the International Journal on Advances in Intelligent Systems, the Journal of Mathematics in Engineering, Science and Aerospace (MESA) and the International Journal of Aeronautical and Space Sciences. Professor Tsourdos is a member of the Expert Advisory Group on Precision, Navigation and Networking for the Complex Weapons Centre of Defence Technology, a member of the A|D|S Autonomous Systems Strategy Group and the ADD KTN National Technical Committee on Autonomous Systems. Professor Tsourdos is also a member of the IFAC Technical Committee on Aerospace Control, the IFAC Technical Committee on Networked Systems, the AIAA Technical Committee on Guidance, Control & Navigation (AIAA GNC TC), The AIAA Unmanned Systems Programme Committee, the IEEE Control System Society Technical Committee on Aerospace Control (TCAC) and the IEEE Technical Committee on Aerial Robotics and Unmanned Aerial Vehicles. Professor Tsourdos is also member of IET Robotics & Mechatronics Executive Team. He is co-author of the book "Cooperative Path Planning of Unmanned Aerial Vehicles" and over 100 conference and journal papers.

Description of the intended audience:

- Graduate students and researchers in electrical engineering, mechanical & aerospace engineering interesting in UAS and fault-tolerant control and cooperative control.
- Researchers on UAS/UAV investigation and development; interesting in new techniques on fault diagnosis, health management, fault-tolerant guidance, navigation and control, and cooperative guidance, navigation and control.
- Managers, practitioners and developers on UAS, and with interests to fault diagnosis, health management, fault-tolerant guidance, navigation and control, and cooperative guidance, navigation and control.
- Researchers or engineers in the fields of surveillance, search, rescue missions, geographic studies, military and security applications interesting in the use of UAS/UAV.
- Since the proposed workshop is currently an interesting and active research topic, one of evidence is that one of presenters, Dr. Zhang's survey paper on *Bibliographical Review on Reconfigurable Fault-tolerant Control Systems* published in 2008 at IFAC "Annual Reviews in Control" gains the highest citation among the articles published in the last five years and even in the history of the journal, it is expected there are more than 30-50 enrollments for the workshop.

Workshop outline (A full-day workshop) (List below is not in the final sequence of presentation)

- Introduction to Fault-tolerant Control and Cooperative Control: Motivation, Concept, History, Existing and Future Developments, and Applications to a Multiple Quadrotor UAVs Testbed (Dr. Zhang)
- Health Management for Persistent Surveillance: Theory and Practical Results (Dr. Rabbath)
- Fault-tolerant Control of a Fixed-wing UAV Testbed (Dr. Chen)
- Sliding Mode Schemes for Fault Detection and Fault Tolerant Control (Dr. Edwards)
- Tools for Teaching Autonomous Unmanned Vehicle Systems (Mr. Fulford)
- A Passive Fault Tolerant Flight Control for Maximum Allowable Vertical Tail Damaged Aircraft (Dr. Liu)
- Methodologies for Adaptive Flight Envelope Estimation and Protection with Application to NASA's GTM UAV under Upset Flight Conditions (Dr. Tang)
- Design of Fault-tolerant Control Methods Based on Reliability (Dr. Theilliol & Dr. Zhang)
- Multiple UAS Operations: Toward Verifiable Autonomy (Dr. Tsourdos).

Workshop abstract (List below is not in the final sequence of presentation)

- Introduction to Fault-tolerant Control and Cooperative Control: Motivation, Concept, History, Existing and Future Developments, and Applications to a Multiple Quadrotor UAVs Testbed (Dr. Zhang)

  Unmanned systems including Unmanned Aerial Vehicles (UAVs) are gaining more and more attention during the last few years due to their important contribution and cost effective application in several tasks such as surveillance, search, rescue, military and security applications. A team of researchers at the Department of Mechanical and Industrial Engineering of Concordia University, with the support from three Canadian-based industrial partners (Quanser Inc., Opal-RT Technologies Inc., and Numerica Technologies Inc.), have been working on a Networked Fault-Tolerant Cooperative Autonomous Vehicles (NFTCAV) research project as well as for "Flight Control Systems" and "Fault Diagnosis and Fault Tolerant Control Systems" courses teaching using multiple quadrotor helicopter UAVs. The main objective of the project is to provide theoretical and experimental results on on-line and on-line UAV modeling, cooperative decision-making and tasks assignment, trajectory and path planning, formation flight, fault diagnosis and fault-tolerant control, and at the same time to transfer quickly the research outcomes to the undergraduate and graduate courses teaching. A set of unmanned vehicles testbeds with several quadrotor UAVs have been built at the Department of Mechanical and Industrial Engineering of Concordia University based on the financial support of NSERC (Natural Sciences and Engineering Research Council of Canada) since 2007, with the help of Quanser Inc. for the testbed development.

  In this presentation, brief introduction to the concept on fault-tolerant control and cooperative control will be given first. Historical development and new challenges in this active research area will be outlined. An overview of our past, current and future research activities and research outcomes on fault diagnosis, fault-tolerant control, path and trajectory planning/re-planning and cooperative control with applications to unmanned systems including the quadrotor helicopter UAV, NASA's GTM fixed-wing UAV and an Airbus A380 model UAV, will be presented.

- Health Management for Persistent Surveillance: Theory and Practical Results (Dr. Rabbath)

  We present the problem of coverage of an area with a team of aerial robotic drones. The drones self-position themselves to maintain coverage, thus removing the burden of multi-vehicle control and management from the human operator. The drones have the ability to adapt their position in case adverse events take place during the course of an operation. Adverse events include the loss of one or more robots, inter-vehicle communication problems, intruders entering the area being monitored, and loss of effectiveness of one or more robots. We present the step-by-step design of such intelligent system, and importantly illustrate the performances obtained by means of indoor, controlled experiments with a small team of quadrotor drones. Videos are an integral part of the presentation. Hardcopy notes will be given to the audience. In this presentation, the concept of health management is defined, and current systems enabling team coordination in case of health problems are discussed. Part of the presentation relates to the first book on safety and reliability for teams of robotic drones recently published by the speaker, and entitled “Safety and Reliability in Cooperating Unmanned Aerial Systems”.

- Fault-tolerant Control of a Fixed-wing UAV Testbed (Dr. Chen)
  In order to guarantee the reliability and performance of UAV, there are some redundancies in the design of UAV. But too many redundancies will require a hard condition on the payload of UAV. This presentation aims at providing recommendation on what kind of faults in actuators are forbidden that we should make a backup in the design of UAV and what kind of faults are allowed without affecting the performance of UAV. It is common that when design a feedback controller the physical property of system are often overlooked. In this presentation, we put the 'physics' of UAV back in the design of fault tolerant controller for fixed-wing test-bed and we try to find what are the maximum faults that can be tolerated in this kind of UAV. Theory of cascaded system and under-actuated systems are used to realize the hovering of VTOL. Simulation results with different faults are also presented to validate the effectiveness of the presented fault tolerant controller.

- Sliding Mode Schemes for Fault Detection and Fault Tolerant Control (Dr. Edwards)
  Sliding mode methods have been historically studied because of their strong robustness properties to a certain class of uncertainty. This is achieved by employing nonlinear control/injection signals to force the system trajectories to attain in finite time a motion along a surface in the state-space. The associated reduced order dynamics, whilst constrained to the surface is called the sliding motion, and possess strong robustness properties. This talk will consider how these ideas can be exploited for fault detection (specifically fault signal estimation) and subsequently fault tolerant control. The talk will also describe an application of these ideas to aerospace systems. It will describe flight simulator results associated with the EL-AL 1862 Bijlmermeer scenario studied as part of the GARTEUR AG16 action group on fault tolerant control. The controller design was carried out without any knowledge of the types of faults/failures occurring on the aircraft, and employs sliding mode methods. The results demonstrate the successful real-time implementation of the proposed fault tolerant control scheme on a motion flight simulator configured to represent the EL-AL aircraft.

- Tools for Teaching Autonomous Unmanned Vehicle Systems (Mr. Fulford)
  Unmanned Vehicle Systems (UVS) are growing in popularity across a broad spectrum of applications such as search and rescue, military, mining, and environmental surveillance. Likewise, the UVS research community is growing and there is an increasing demand for novel hardware and software platforms on which to develop and test UVS algorithms and controllers.

  To meet the growing demand for new technologies to teach and develop the next-generation unmanned systems, this workshop presents the latest technologies for UVS teaching and research. As part of this workshop, we will review how leading universities have integrated autonomous unmanned systems into their teaching and research programs using this state-of-the-art rapid controls prototyping framework and open-architecture data acquisition hardware designed for unmanned systems. This workshop will also demonstrate how innovative hardware-in-the-loop systems can be used to augment virtual 3D UVS missions in order to teach fundamental control concepts while motivating students with exciting, real-world UVS applications. More advanced concepts will be introduced with specific focus on tools for autonomous unmanned vehicle systems. Demonstrations will show autonomous unmanned vehicle missions planned out and executed in simulations with rendered 3D visualization.

  Topics and Target Audience
  - Autonomous unmanned systems for teaching and research
  - Rapid control development tools
  - Real-time control
  - Tools for simulation and operation

- Curriculum for unmanned vehicle systems

- A Passive Fault Tolerant Flight Control for Maximum Allowable Vertical Tail Damaged Aircraft (Dr. Liu)
  It investigates a passive fault tolerant control to aircraft that suffers from vertical tail damage. A novel notion of damage degree is introduced to parameterize the damaged flight dynamics model. It is applied to seek the maximum allowable damage degree (tolerance capacity) stabilizable by the proposed passive fault tolerant and backup control under a linearized model. The design algorithms are presented and illustrated through numerical simulations on one aircraft model. Furthermore, the impact of potential control saturation is taken into account in the proposed design and a set of design parameters are tuned such that the maximum allowable damage degree is bounded, represented as the so-called critical damage degree.

- Methodologies for Adaptive Flight Envelope Estimation and Protection with Application to NASA's GTM UAV under Upset Flight Conditions (Dr. Tang)
  This presentation reports the latest development of several techniques for adaptive flight envelope estimation and protection system for aircraft under damage upset conditions. Through the integration of advanced fault detection algorithms, real-time system identification of the damage/faulted aircraft and flight envelop estimation, real-time decision support can be executed autonomously for improving damage tolerance and flight recoverability. Particularly, a bank of adaptive nonlinear fault detection and isolation estimators were developed for flight control actuator faults; a real-time system identification method was developed for assessing the dynamics and performance limitation of impaired aircraft; online learning neural networks were used to approximate selected aircraft dynamics which were then inverted to estimate command margins. As off-line training of network weights is not required, the method has the advantage of adapting to varying flight conditions and different vehicle configurations. The key benefit of the envelope estimation and protection system is that it allows the aircraft to fly close to its limit boundary by constantly updating the controller command limits during flight. The developed techniques were demonstrated on NASA's Generic Transport Model (GTM) simulation environments with simulated actuator faults. Simulation results and remarks on future work are presented.

- Design of Fault-tolerant Control Methods Based on Reliability (Dr. Theilliol & Dr. Zhang)
  Faults or failures such as defects in components, instruments, controllers and/or control loop can cause undesired reactions and consequences such as damages to technical parts of the plant, to human life or to the environment. Traditionally, the objective of Fault Tolerant Control System (FTCS) is to maintain its current performance close to the desired one and preserve its stability conditions despite of component and/or instrument faults; in some circumstances a reduced performances may have to be accepted as a trade-off leading to a sub-optimal outcome. Design of control systems to achieve fault-tolerance for closed-loop control of safety-critical systems has been an active area of investigation for many years. It becomes more and more clear that there are certain trades-offs between achievable normal performance and fault-tolerance capability. However, despite of the many efforts in control community, most of the contributions did not consider or take into account the reliability of components, algorithms or soft computing structures to guarantee such performance and to reduce the gap between nominal and faulty case. This contribution aims at presenting new and innovative research results on how to design Fault Tolerant Control Systems with particular attention to consider and combine reliability analysis in the design procedure and/or real-time control synthesis. Current and future research is presented in order to solve the above challenging research problems devoted to safety-critical systems such as flying vehicles, unmanned aerial vehicles (UAVs), missiles, airships etc.

- Multiple UAS Operations: Toward Verifiable Autonomy (Dr. Tsourdos).
  There are many applications using autonomous systems such as unmanned aerial vehicles: surveillance/attacking, traffic monitoring, search and rescue, and so on. Nowadays the applications and missions become so various and complex that the systems become more complicated. Those missions are

related not only with civil purpose but also with military one so usually safety-critical. Diverse sensors are equipped in the systems for safety and redundancy, furthermore, a group of autonomous systems has been recently considered for more effective mission performance. As the systems are complicated, reliability of systems must be verified at the design level. There are some methods to verify the reliability of systems at the design level such as a simulation in a virtual environment, a test with a mock-up, and formal methods. Firstly, test with a mock-up costs a lot of money and time to perform and doesn't always guarantee the safety during it processes. Simulation costs less money and time than for the test, but it is not always easy to consider all the possible scenarios and situations. In contrast formal methods are based on solid mathematical techniques and offer quantifiable answers to questions related with reliability of systems, and thus they are widely used to verify the safety-critical or high-autonomy systems. Model-checking is an automatic technique based on formal methods for verifying finite state system. It checks whether the system satisfy the properties or not automatically. There are three parts of process in model-checking: modeling, specification, and verification. This contribution aims at presenting new and innovative research results on how to model multiple UAS systems as multi-agent systems using formal methods to captures their specifications that would enable to validate their performance and finally how to verify their performance in the presence of faults.

Workshop materials:

To be delivered to participants during and before workshop with the presentation slides, notes and other necessary supporting documents.

Workshop references (Author with **bold face** is one of the speakers at this workshop):

- Halim Alwi, **Christopher Edwards**, and Chee Pin Tan, *Fault Detection and Fault Tolerant Control using Sliding Modes*, Springer, 2011.
- **Antonios Tsourdos**, Brian White, and Madhavan Shanmugavel, *Cooperative Path Planning of Unmanned Aerial Vehicles*, Wiley, 2011.
- **Christopher Edwards**, Thomas Lombaerts, and Hafid Smaili (Eds.) *Fault Tolerant Flight Control: A Benchmark Challenge*, Springer, 2010.
- **Camille-Alain Rabbath** and Nicolas Léchevin, *Safety and Reliability in Cooperating Unmanned Aerial Systems*, World Scientific Publishing, 2010.
- Hassan Noura, **Didier Theilliol**, Jean-Christophe Ponsart, and Abbas Chamseddine, *Fault-tolerant Control Systems: Design and Practical Applications*, Springer, 2009.
- Mufeed Mahmoud, Jin Jiang, and **Youmin Zhang**, *Active Fault Tolerant Control Systems: Stochastic Analysis and Synthesis*, Springer, 2003.
- **Youmin Zhang** and Jin Jiang, Bibliographical Review on Reconfigurable Fault-tolerant Control Systems, *Annual Reviews in Control*, vol. 32, no. 2, Dec. 2008, pp. 229-252 (Ranked No. 1 in the "Top 10 Cited" and No. 6 in "Most Downloaded" articles published in the last five years at the journal).
- Other references will be provided during the workshop to participants.