MAKING SPACE FOR EVERYONE: A RESEARCH PROGRAM AIMED AT BREAKING DOWN BARRIERS TO NEW TECHNOLOGY ADOPTION IN SPACE

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Abstract

Over the past 50 years, the space industry has been hesitant to adopt many of the most cutting-edge advances in satellite research. As a result, these missions continue to cost hundreds of millions of dollars and take close to a decade to design and build spacecraft prior to launch. This paper introduces a collaborative, interdisciplinary research program to overcome some of the barriers that prevent the space industry from implementing new technologies. This research aims to improve the reliability of space missions and reduce the cost and design cycle time by addressing key aspects of space systems design. Firstly, resilient spacecraft control systems will be developed by investigating safe, self-configuring and adaptive satellite control strategies that reduce development time by eliminating the need for simulation, characterization or calibration prior to launch. Second, robust and scalable "cloud-based" navigation solutions will be developed that can leverage knowledge of existing space objects to help control satellite position and orientation in orbit. Third, smart technologies will be developed for harsh space environments that can be embedded into multi-function structural spacecraft panels to provide protection from launch vibration, radiation and small particles. A multi-vehicle drone testbed will be developed to evaluate, characterize and demonstrate these technologies without resorting to a full satellite launch. During this program, students will work with Magellan Aerospace to understand the challenges of satellite engineering and design and build a technology demonstration satellite mission in the jointly-owned Advanced Satellite Integration Facility. The enabling technologies developed in this research program will make space engineering more relevant to today's engineering state of the art and make space more accessible to Canadian companies and research institutions.

Introduction

Space exploration and the commercial use of space provides a demonstrated wealth of opportunities for academia and industry, ranging from basic physics research[1-5] to geology[6-9], security[10-13], agriculture[14-19], communications[20-23], astronomy[24-28], tourism[29-32] and even remote mining[33,34]. However, while humans have been exploiting space for more than half a century, many space companies have been slow to adopt new technologies, despite considerable advances by prominent Canadian and international space researchers[35-40]. Fear of the untested has resulted in a general industrial reluctance to incorporate modern engineering technologies such as robust, adaptive control, smart structures, advanced multi-sensor data fusion, composite manufacturing and other cost-saving advancements that promise to revolutionize our access to space by reducing the cost of engineering development and shortening the time from mission conception to mission execution.

A. de Ruiter has done considerable research recently on satellite dynamics and control[38-40]. Unfortunately, most commercial satellites have not adopted many new control strategies since Lefferts et al.[41] and Kalman [42,43] published their works on spacecraft attitude estimation and control. Since then, there have been considerable advancements in on-line parameter estimation[44], robust control[45-47], adaptive control[48,49] and the recently resurgent fractional calculus control[50-52], but very few of these technologies have become prevalent in the commercial space industry. There have also been tremendous advancements in multi-sensor data fusion[54,55], particularly using decentralized[56,57] estimation approaches. Automobiles[58,59], home appliances[60] and even thermostats[61] have all adopted modern control systems to keep up with evolving technology trends while continuing to reduce the time from product conception to market and further reduce prices. The space industry has not followed suit. However, with appropriate adaptation and the requisite qualification the space industry requires, these modern control and estimation technologies can eliminate much of the design and characterization efforts typically spent in most space mission design programs, resulting in lower mission cost and faster mission execution.

From a manufacturing perspective, almost every commercial spacecraft since Sputnik has been assembled in the same way. Advancements towards modular spacecraft have been made[80,81] to enable faster spacecraft integration, and some researchers have explored composites for main structural assembly[37]. However, aluminum (particularly AA-6061) continues to be the mainstay of commercial spacecraft manufacturing, using a sturdy aluminum shell with honeycomb panels and platforms, upon which a multitude of equipment including power control systems, computers, fuel tanks and reaction wheels are attached[62]. If additional environmental protection such as thermal blankets, radiation shielding or micrometeoroid protection is required, layers upon layers of even more aluminum or Mylar are added until the risk of environmental damage is deemed to be low enough[63]. The aircraft industry, in contrast, has shifted from largely aluminum construction to more and more composites with embedded electronics, in response to an industry demand to reduce costs, improve fuel economy and provide easier access to air travel[64]. Through appropriate research, prototyping and demonstration, this research program aims to apply these same modern technologies to the space industry, thereby reducing the total mission cost and improving access to space. This interdisciplinary research program applies today's most promising technologies and use them to demonstrate their efficacy and to reduce the cost and protracted schedule of commercial and academic space missions.

Research Plan

The specific goal of this research is to develop, validate and standardize a set of satellite guidance, navigation and control technologies aimed at lowering the cost, improving the reliability and shortening the lead-time of the Canadian and international satellite industries. Working closely with Magellan Aerospace, a proven leader in space systems design, development, manufacturing and operations[65-68], this research will address some of today's key challenges that force many commercial space missions into five-to ten-year schedules that cost hundreds of millions of dollars.

Project 1: Resilient Control Systems

The objective of this research project is to develop and validate globally stable adaptive satellite control methodologies that require little to no configuration or simulation prior to launch. While many may argue that the combination of a Kalman filter plus a finely tuned PID controller works well, it only does so after meticulous fine tuning, unique to each individual satellite, to achieve specific performance across all mission phases and accounting for errors introduced by linearization or unmodeled phenomena such as fuel slosh.

Another key aspect of spacecraft control is the ability of the spacecraft to "bootstrap" itself. Following separation from the launch vehicle, many spacecraft end up in a critical state that is extremely prone to error. Satellites must detumble themselves (typically using standard "B-dot" controllers[70]), deploy solar arrays (if applicable) and ultimately put themselves into a safe power state that keeps batteries charged. The critical nature of this early mission phase leads many mission designers to spend extensive resources on designing unique and complex systems to ensure safe orbit injection, taking into account: off-nominal launch vehicle separation, potential impacts on power system stability and control system hardware or software failures.

The above challenges require that today's space systems engineers plan for every possible eventuality. Months of attitude and orbit simulations are required to confirm performance and mitigate risk due to component failure. However, while these simulations and studies are time-consuming and expensive, they still only provide assurances to predictable eventualities and are typically only applicable to a specific spacecraft configuration. The satellite industry requires more advanced control system technologies that do not require specific planning and tuning prior to every launch. Further, the satellite industry requires these new technologies be proven and qualified over a variety of implementations to support widespread adoption and acceptance by a traditionally risk-averse industry.

Hypotheses:

1-A: Modern non-linear estimation and control technologies such as fractional calculus can be used to model and adapt to challenging non-linear aspects of satellite control, including fuel slosh and atmospheric drag (particularly applicable to low-altitude small satellite missions).

1-B: Modern, adaptive / robust control and estimation theory can be applied to satellite control such that a satellite can configure itself on-orbit to changing environments and vehicle dynamics, as well as biases and scale factors in sensors and actuators, thereby removing the need for most costly calibration and measurement activities prior to launch.

1-C: Generalized adaptive and non-linear control schemes for satellites can be proven to be globally stable for any satellite architecture, thereby removing the need for exhaustive and time-consuming simulations prior to launch.

1-D: By taking advantage of natural dynamics, avionics design and solar panel arrangement, simple rules for spacecraft design can be defined that ensure safety following spacecraft separation for any spacecraft in any scenario.

Methodologies:

This research explores specific estimation and control technologies, and fractional calculus (involving the continuum of derivatives and integrals beyond simple integers) holds particular promise in this regard. Fractional calculus has been a very useful tool for modeling non-linear phenomena like slipping and friction[50]. Fractional calculus has also been used to control and identify dynamic systems using fractional derivatives and integrals instead of the more common PID controllers, in an attempt to obtain finer control[51]. The research team plans to apply fractional PID control and estimation to spacecraft that experience non-linear drag or fuel slosh dynamics, which are difficult to model with traditional methods. The team will investigate novel ways of handling spacecraft nonlinearities using fractional calculus.

The research team will work closely with Magellan Aerospace to model all aspects of time-consuming satellite characterization, calibration and measurement prior to launch. Modern adaptive and robust control strategies will be prototyped and evaluated for their ability to reduce or eliminate the need for pre-launch characterization.

A key part of this analytical work will involve the balance between a simulated demonstration of stability and a conclusive and global mathematical proof that the control strategy is stable. Since the purpose of this research program is to reduce development and test time, it is important that one can conclude general stability characteristics without the need for exhaustive simulation. Monte Carlo simulations can demonstrate stability over a variety of operating conditions, but the best kinds of stability demonstrations are analytical in nature. To this end, the team will build upon recent analytical Lyapunov techniques developed by de Ruiter[38,69] to demonstrate global stability of the control strategies developed prior to physical demonstration.

Studying and evaluating inherently safe satellite designs will begin with a fundamental definition of safety using a classic reliability analysis (following the industry standard for systems reliability, MIL-HDBK-217F). Using this analysis as a basis, this research will define certain design parameters such as solar panel coverage, dynamic stability, controllability and redundancy and then optimize to determine the safest generic spacecraft design in terms of its ability to bootstrap itself following even the most anomalous separation events. The team will also work closely with Magellan Aerospace to understand the key cost and schedule drivers of recent space programs, using actual project management data. By estimating the impact of the above advancements, we will quantify the cost, schedule and reliability improvements these technologies would bring to future satellites.

Project 2: Innovative Multi-Sensor Data Fusion

<u>The objective of this project is to develop robust navigation algorithms that use Resident Space Objects (RSOs) to both navigate and orient a satellite in earth orbit</u>. Spacecraft navigation and controls engineers are accustomed to extracting data from multiple sources in an effort to accurately determine a spacecraft's attitude, attitude rates and orbital parameters[41]. Star positions, gyros, accelerometers, sun sensors, earth horizon sensors, magnetometers and GPS receivers are all common sensors used for spacecraft navigation and control.

As space commerce continues to grow, so does the density of space assets in "popular" orbits (low earth orbit, polar orbits, sun synchronous orbits and geostationary orbits)[71]. These assets mostly include spent rocket bodies and satellites (many have been inactive for years or decades). Similar to the meticulous measurements astronomers take to map the location of stars in the sky[72], space researchers and military organizations measure and track orbital parameters of most RSOs larger than 5 cm in diameter[73,74].

On a small scale, the concept of using other space assets to assist in navigation is not new. As part of his Master's research at MIT, Dr. Ferguson studied ways in which a fleet of cooperative spacecraft could decentralize their fleet state estimation (orbital determination) using GPS and local transmitters that measured the distance and velocity (using Doppler measurements) between every pair of spacecraft in the fleet[56,57]. The question this research team now aims to explore is how to extend this technology beyond local cooperative spacecraft, to the RSO population, enabling "Cloud-based Space Navigation".

Hypotheses:

2-A: A combined attitude and orbit estimator can be developed using observations from space objects with known orbital properties.
2-B: Radio transmissions from existing space objects can be used as a means of detection, identification and navigation through cross-reference with known catalogues of space objects.
2-C: A small, low-power radio transponder can be used to improve navigation from space objects.

Methodologies:

The first challenge in making use of RSO navigation information is in detecting the RSOs. In some instances star trackers can detect RSOs, but only if they are sufficiently reflective and are in proper opposition[75]. However, if they are detected and identified through cross-reference with the RSO catalogue, a lot of information can be gleaned. The research team is collaborating with Defence Research and Development Canada (DRDC) to develop a suitable RSO model in support of this research. Unlike a star tracker that only detects stars assumed to be "at infinity", the position of an RSO with respect to the sensor on the satellite changes as a function of the orbital position. This orbital position as well as attitude dependence means that, theoretically, the star tracker could provide orbital knowledge in addition to the traditional attitude knowledge typically assumed for star trackers.

Given the difficulty in visually detecting RSOs, the team plans to also investigate the possibility of detecting radio transmissions from RSOs as a means of localization. Since most RSOs use radios to communicate with the ground, a certain percentage of RSOs may still have active radios on-board and may still be transmitting. Radio heartbeats or other spurious transmissions may be detectable by wideband receivers. Detection and tracking over various timescales, along with a Doppler / frequency analysis of the signals may enable localization through specialized Kalman filters. This will require cross-referencing with RSO catalogues and some prior knowledge of which RSOs may have active transmitters, but localization should be possible.

While passive radio detection may be possible in certain cases, it is likely that "cloud-based navigation" may only be feasible in a general sense by outfitting future RSOs with a small, inexpensive radio beacon to be used for localization purposes. This beacon could be entirely self-powered and encoded with a unique number, representing the RSO's catalogue identifier. The catalogue identifier would eliminate the need to identify which RSO has been detected. Further, with control over the exact signal produced by the radio beacon, it could be optimized (through appropriate industrial and inter-departmental collaboration) for ease of detection / localization. To this end, the research team will study, design and prototype a purpose-built beacon for navigation purposes.

Project 3: Smart Technologies for Harsh Space Environments

<u>The objective of this research project is to leverage modern advances in composites manufacturing and microelectromechanical systems (MEMS) to develop spacecraft structural panels that include embedded attitude sensors, actuators and communications antennas</u>. Physical accommodation and protection of sensitive avionics is a significant challenge for satellite engineers as bulky reaction wheels, sensors and cabling take up valuable space that could be used for a payload. Space radiation, launch vibration, thermal extremes and micrometeoroids also pose significant risks to sensitive spacecraft control equipment. Standard practice in the space industry has been to merely add thicker aluminum walls[63], but this has been shown to be not as effective as originally thought (due to secondary radiation), from both a mass and protection perspective[76,77]. For most space missions, the mechanical engineering team works relatively independently of the electrical and controls teams, except for the communication of mass properties

estimates. The satellite industry needs unified engineering approaches that solve mechanical, electrical and navigation challenges with multi-function structures.

Fortunately, research by Dr. Jayaraman at the University of Manitoba has led to a novel composite radiation shield for satellites in high-radiation orbits[67,78]. Dr. Telichev (also from the University of Manitoba) has further advanced this field by studying the effect of micrometeoroid and space debris impacts on composite structures in space, suggesting new mechanisms for protection[79]. By combining the structural panels with radiation shielding, attitude control and communication, spacecraft resources become much more efficient, leaving more time and resources for designing, accommodating and integrating the most important part of any spacecraft – the payload.

Hypotheses:

3-A: By combining modern composite manufacturing methodologies that layer different types of materials together with recent advancements in miniature motor and electronics design, a spacecraft panel can be designed that contains a complete cadre of attitude control sensors, actuators and communications antennas.

3-B: Using pre-assembled, multi-function panels with embedded attitude control and communications hardware can reduce the satellite design and manufacturing timelines by as much as 15%.

3-C: Using pre-assembled, multi-function panels with embedded attitude control and communications hardware can increase the volume available for payloads by as much as 25%.

Methodologies:

The vision for a multi-functional spacecraft panel involves a single panel with embedded electronics, shielding, sensors and actuators that all come out to a single connector panel for integration with the rest of the spacecraft (thereby eliminating much of the sensor and actuator cable harnessing that complicates most spacecraft bus cavities today). To achieve this, there are a number of key challenges that must be researched, prototyped, tested and validated, drawing upon a variety of research partners. This plan represents a broad collaborative effort, involving the space systems design, manufacturing and testing expertise / facilities at Magellan Aerospace, product assurance representatives at the Canadian Space Agency as well as other researchers from within the University of Manitoba, Faculty of Engineering. Current research is focused on embedded antenna arrays, harnessing and actuators (torque coils and miniature reaction wheels embedded within panels).

The multi-function panel research requires a clear understanding of the mechanical properties (particularly stiffness) to ensure space mission suitability. As such, researchers will manufacture test panels in the University of Manitoba Composite Materials and Structures Labs. Using expertise and tools at Magellan Aerospace, the team will also estimate the thermal properties of the panel. Altering the thickness of the honeycomb core and changing the reflectance / emissivity of the coating will affect the stiffness and thermal properties as required.

With an understanding of the stiffness characteristics, the research team can begin designing low-profile reaction wheels and sun sensors to be embedded into the panels. The challenge with this research will be identifying small motors and bearings that can fit into a thin cross-section, while still providing sufficient torque and momentum storage. Solid modeling will provide inertia estimates and electro-mechanical modeling of the motor, drive circuit and rotor will provide torque and momentum storage estimates (including a prediction of the torque/speed behaviour of the device). Students will assemble prototypes of the panel-embedded wheels and torque coils and then conduct torque, stability and momentum storage tests using small force / moment tables. The team will follow a similar procedure with the attitude sensors and antennas (using the University of Manitoba's Antenna Laboratory in the Department of Electrical and Computer Engineering). They will then subject the panels to thermal, vacuum and vibration extremes using Magellan's facilities. Small versions of the test panels will be assembled and integrated into the drone testbed (see Project 4) for end-to-end integration in a test spacecraft.

For all electronics and mechanisms embedded into the panels, a clear method of inspection will be required for adoption within the space industry. The research team is working with experts in product assurance at

Magellan Aerospace to advise on non-destructive inspection techniques to verify the quality of hidden wires, connections, bearings and electronics. These inspections will be required prior to and following each environmental test.

Project 4: Multi-Vehicle Drone Testbed

The objective of this research project is to develop an easily accessible testbed for evaluating satellite control hardware and algorithms without the need for costly launches or microgravity emulators. A key challenge with control system development for satellites is performance verification on representative hardware. Satellite engineers rely on high-fidelity simulation to ensure adequate performance. In extreme cases, parabolic flight has been used[88] to mimic microgravity, however those experiments are costly, difficult to schedule, and can only last for approximately 25 seconds at a time. A testbed located at the University of Manitoba with an intuitive software interface for rapidly prototyping and validating new control technologies will support easy and inexpensive control systems research that can be completed within the timelines of this research program.

Hypotheses:

4-A: Consumer drones can be programmed with nested control loops, providing sufficient abstraction to enable independent control system development in a simulated dynamic environment.

4-B: Consumer drones can be augmented with devices that enable independent rotational and translational motion in six degrees of freedom.

Methodologies:

The research team is developing a multi-vehicle drone testbed to emulate the space guidance, navigation and control environment. The drone testbed will consist of three to four copter-style drones with six-axis control (employing a rotational gimbal at the center). Using an off-the-shelf autopilot, the team will stabilize the platform using onboard sensors. Next, they will wrap a controller around the autopilot that will cause the drone to behave as if it were in a different dynamic environment. For example, they could make the drone behave as if gravity were inverted, or, as if it were attached to an elastic band tethered to the ground. For the purposes of this research, the team will program zero gravity for single spacecraft control investigations. For multi-spacecraft control investigations, they will use Hill's Equations for representing the relative motion of one spacecraft with respect to another in neighbouring orbits.

With the drone behaving like a spacecraft, the research team will apply a third layer of control around the artificial dynamics described above. This third level will be the controller or estimator the team is evaluating, using only the sensors and actuators assumed to be available on the spacecraft. This multi-vehicle drone testbed will become a key test facility that will be used by many research or industry groups for testing dynamics that are difficult to replicate on Earth.

Several key challenges such as drag, downwash and drone-to-drone interference will need to be addressed to remove the drone-specific dynamics from the testbed, leaving only spacecraft dynamics. To tackle these challenges, the team plans to perform controlled system identification exercises to model, and compensate for gravity, inertial effects, viscous drag and turbulence caused by neighbouring drones. Constraints on the proximity of one drone to another may be required both for safety and to prevent interference. The research team will develop the testbed in a staged approach, starting with translational dynamics first and then progressing to attitude dynamics. Since most drones available on the market today do not have enough degrees of freedom to control attitude independent of position and velocity, an active gimbal will likely be required below the drone to provide the attitude dynamics emulation.

Project 5: Technology Demonstration CubeSat

The objective of this research project is to combine all candidate technologies developed as part of this research program into a single demonstration CubeSat, providing a means of formally qualifying the technologies for future satellite programs. While the multi-vehicle drone testbed will enable rapid testing of control algorithms on real hardware without having to wait for launch opportunities, there is still tremendous value in performing environmental tests on a fully assembled demonstration spacecraft, particularly when convincing space agencies of a certain Technical Readiness Level (TRL)[82]. Further, the integration and test effort can and likely will illuminate complex interactions between new technologies that would not have been uncovered during subsystem evaluation.

Hypothesis:

5-A: End-to-end systems integration and test of a complete CubeSat mission, incorporating most elements of this research program, will demonstrate a measurable reduction in cost and schedule for the satellite design, integration and test program over similarly scoped CubeSat missions.

Methodologies:

Throughout this research program, the research team plans to lead a CubeSat assembly project to demonstrate and qualify the key technological advancements this research program develops. The mission will follow an abbreviated design / build / test cycle with close industrial collaboration. Early in the design phase, the research team will identify the technologies slated for demonstration, as well as a particular Principal Investigator who has a scientific need for a short space mission using a nanosatellite. For spacecraft integration and test, the team will use the Advanced Satellite Integration Facility (ASIF) with assistance from Magellan. The CubeSat will also provide opportunities to evaluate the effect the new technologies have on the mission and spacecraft design / build / test timeline and cost.

In addition, the value of the technology demonstration satellite will extend beyond the duration of the research program and will help to promote a continuation and further expansion of satellite research at the University of Manitoba. The intent will be to use the satellite to build toward a future demonstration launch that can provide critical spaceflight heritage to the developed technologies. In addition, collaborations will be established with scientists from other disciplines who could collect valuable data to support their research by contributing a research payload that can be incorporated into the satellite.

Conclusion

Most engineering disciplines have seen dramatic advances in the past few decades in the areas of low-cost manufacturing, smart / adaptive controllers and cloud-based "big-data" computing. Unfortunately, due to the risk-averse nature of spaceflight (brought on by the onerous cost and schedule typically associated with space missions), the space engineering discipline has been reluctant to adopt new technologies. This research aims to break down the barriers that are holding back space engineering. With rigorous stability and safety analyses / proofs, adaptive and "learning" controllers *can* be used effectively on space missions without thousands of hours of simulations ahead of each launch. With appropriate research, composite manufacturing *can* become a viable part of any satellite. These new technologies will make today's engineering state-of-the-art more viable in the satellite industry.

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