Special Topic – Independent Study (for up to 6 students)

Title: Rocket Systems Engineering

Introduction:

A common problem with model rockets is that depending on conditions, they can lose direction and veer far off course, sometimes preventing recovery. To reach significant predetermined altitudes and position requires accurate control systems and inertial sensors which are typically expensive. A solid fuel powered rocket has been developed and successfully launched, but suffers from instability particularly during the first few seconds after take off.

The aim of this project is to combine modelling and simulation of rocket dynamics with real experiments to develop a robust control system and minimize the cost of the inertial sensor system. By analyzing the dominating dynamics in a specific direction or orientation, single input, single output type control systems will be developed, simplifying implementation and reducing the required sensors. For example controlling the angular rate to zero using a rate gyro, accelerometers could be used to correct for the remaining drift, avoiding the use of GPS.

Hypothesis: Analysis and modelling of the major dynamics of a rocket and smaller scale test rigs will improve the control of rockets at a reduced cost.

Methodology:

This project will utilize dynamic modelling and simulation, a small scale test rig and a DC motor powered rocket to assist in the design of a control system for an existing solid fuel rocket. This test rig will involve a vacuum pump and an oval shaped (with pointed ends) object pivoted vertically from the pump. Actuation surfaces will be placed on the object, and the movement of the air past the object will simulate the rocket in flight. The shape and set up will be optimized to approximate the dynamics of the full scale rocket and will help minimize the amount of test flights required. It will also provide significant data for validating the modelling methodologies developed as well as testing simplified control strategies that minimize the sensors required.

The results from the test rig will be carried over to a DC motor powered rocket (with Lithium batteries), to help bridge the gap to the solid fuel rocket, minimizing the number of full-scale tests and hence costs. Therefore, there will be three main areas to be investigated which will be broken down into smaller areas to provide an individual focus for each student. An approximate structure for the methodology which could be reduced as required depending on numbers of students involved and time/resources available, is outlined:

Small-scale test rig

- Use a vacuum pump to move air past actuation surfaces in an appropriately shaped object to simulate dynamics of a rocket
- Allow rotation in only one direction. Control angular velocity and analyse how fast the object drifts. Use an accelerometer to measure the drift angle using static theory, and validate with an encoder attached to the pivot of the object which will be on top of the vacuum pump device. Repeat for other direction and then allow full 3D movement.
- Identify transfer function from the input actuation surface angle to the output rocket angle for various air speeds past the rocket
- Tasks involve:
    - Design for pump, actuation surfaces and shape of object
    - Instrumentation and sensors, including encoders, rate gyros and accelerometers, including calibration and development of drift correction methods
    - Modelling and system identification to create a simulation tool for virtual testing of control scenarios and for a formal analysis of dynamics to improve future designs

DC motor powered rocket

- This small scale rocket will reach low altitudes (10-20 m) and allow more realistic tests relative to the solid fuel powered rocket
- Will be constructed based on the significant existing knowledge of DC motor powered helicopters. Initially, the rocket will be stabilized by remote control and used to create data for use in simulation and control system design. The simulated dynamics will also account for disturbances like wind to ensure robustness – a 3rd pro student (Dhruv Rathi) has already agreed to build a radio-controlled DC motor powered rocket regardless of whether or not he is directly involved in the course
- The control system design will feedback to the test rig and vice-versa. Design changes will be implemented as required to better mimic the solid fuel rocket as data becomes available
- The DC motor rocket will be launched for a few seconds then the motor shut off to test safe retrieval, in preparation for a similar test on the main rocket
- Tasks involve:
    - Design of DC motor powered rocket and actuation surfaces

- Instrumentation and sensors, rate gyros and accelerometers, including calibration and development of drift correction methods
- Modelling and system identification to characterize dynamics and to allow accurate comparison to the solid fuel rocket
- Development of control strategies in simulation and time permitting, implementation on the DC motor rocket

<u>Full scale solid fuel powered rocket</u>

- Initially do several launches without a control system and take data for analysis
- Characterize dynamics using modelling and system identification
  - look for dominating directions/orientation
  - in simulation test control on fast pole dynamics first, then alternate with control on slow poles
  - Apply similar designs of actuation surfaces from the test rig and DC motor rocket
- Further improvement of ignition system, customization of thrust parameters and design of motor control system housing
- Development of airbrakes for deceleration of the rocket as well as triggering of recovery system. This work will aim to lift a rocket with scientific payload to the altitude of precisely one mile and implement a robust recovery system for the safe retrieval of the rocket so that the system is reusable. These requirements are based on the NASA University Student Launch Initiative. However, note that this deliverable is <u>not</u> a requirement for this course but serves as <u>motivation</u> for the preliminary work. If it is achieved it will be considered as a bonus.
- The minimum desired outcome from the solid fuel rocket, is that data is obtained with or without an automated control system. Specifically, several movements of the actuation surfaces could be made in at least one flight to allow data to be taken for further development and feedback into potential changes to the test rig and DC motor rocket
- Tasks involve:
  - Design for actuation surfaces (based on test rig and DC motor powered rocket), motor/control system housing and if time permits, air brakes and recovery system
  - Instrumentation and sensors, rate gyros and accelerometers, including calibration and development of drift correction methods
  - Modelling of the major dynamics and system identification of transfer function between characterization of the primary source/direction of instability and development of single input-single output control systems in simulation, and time permitting, implementation on rocket

Minimum overall deliverables

- Small scale test rig, with encoders for validation of rate gyro and accelerometer based sensing and control
  - Fully implemented feedback control system with and without encoder for comparison
  - Virtual simulation tool to capture the test rig dynamics with respect to actuation surface changes and wind speed past the rocket shaped object
- Remote controlled DC motor powered rocket, with sensors to capture motion
- Several launches of solid fuel powered rocket with sensors to capture motion

Optional deliverables (time permitting)

- Automated feedback control system for DC motor rocket and solid fuel rocket, orientation and altitude sensors to capture motion
  - Dynamic model of DC motor rocket and solid fuel rocket responses validated against experimental data
- Safe recovery system for pre-defined height for both DC motor rocket and solid fuel rocket after the motor is shut off

Individual assessment

Literature review - 10 %

- Rocket competitions in other universities internationally
- Commercial interest and skills in demand for aerospace industry
- Analysis of other successfully controlled rockets in other countries, e.g. Taiwan (contacts of Dr Mark Jermy) and analysis of current simulation tools for rocket dynamics
- Structure of any other rocketry courses, e.g. water rockets
- Journal papers on rocket design, control strategies and the required instrumentation/sensors. Characterization of instabilities limits and cost.
- Patent search on rocket stabilizing methods.
- DELIVERABLE: Report and bibliography

Modelling and System Identification - 25 %

- An existing simulation tool for rocket dynamics from Dr Mark Jermy will be the starting point. The student will understand the code and simplify as required to implement on Matlab. This work will involve parameter identification of simpler models using the simulation tool as a "virtual rocket". <u>This simulation tool will provide a backup in case there are unexpected problems obtaining data from rocket and/or test rig experiments</u>
- Extend results to identifying models for the small scale test rig and available data from the DC motor rocket and/or solid fuel rocket
- Development of feedback control strategies in simulation and validation with experimental data if or when it comes available
- Formal characterization of the dynamics and limitations of test rig, and DC motor rocket and/or solid fuel rocket if time permits
- All results will be written up and the matlab code must also be presented, as the quality of the code will contribute 5% to the grade
- DELIVERABLE: Report/code+documentation+working-examples

Individual report on field of expertise - 30 %

- Students will give their choices of what broad area they want to be involved in. Choices are out of the small-scale test rig, DC motor powered rocket and solid fuel powered rocket. Four main subjects within each area will be <u>instrumentation/sensors</u>, <u>rocket shape design</u>, <u>control system development</u> and <u>propulsion system design</u>.
- The choices and extent to what is covered depends on the number of students that enrol and their individual expertise. Note that <u>every student</u> must do the modelling and system identification part detailed above.

Time management/records - 5 %

- Students will keep a work book which will be checked every two weeks and must be typed up and handed in at the end
- Regular meetings and feedback will determine to what extent (if any) the project goals need to be scaled down

Final report - 15 %

- Collates all work with contents page in a miniature thesis type structure or journal draft form
- Includes a minimum 5 page discussion (12 pt, 1.5 line space) on the main elements of their specific area they worked on, and the main discoveries
- Must specify limitations, problems accounted and solutions, deliverables and what improvements are required
- Comments on the effectiveness of the course as a whole, and suggestions for future special topic courses or research. These comments should include the areas they feel they learnt the most, and what motivated them to do the course in the first place.

Individual contribution to rocket poster/display for department marketing purposes - 10 %

Oral presentation - 5 %

- 10 minute presentation for each individual student. 2.5% for the ability to deliver/communicate the material effectively
- 2.5% for the organization of slides

Lecturing: A series of lectures on system identification for ENEL 430, presented by Dr. Hann will be attended. This will give students the tools required to analyse the dynamics of the rocket air frame and design the control system accordingly. Dr. Jermy, Assoc Prof XiaoQi Chen and Dr. Aitchison will be invited to give a 50 minute seminar on their aspect of involvement in the course.

Benefit to the Student: The students will gain the following benefits in this project:

- Valuable understanding of the design and operation of a practical control system with the associated difficulties and challenges
- An added research component to their degree focusing on independent study
- Experience in managing a project with limited budget and fixed deadlines
- Development of skills applicable to the analysis and control system design of aircraft and space flight in general

- Learning the mathematical modelling approaches required to bridge the gap between theory and practice
- Practical experience in the growing field of Mechatronics, including instrumentation, sensor fusion and advanced control
- Unique opportunity to be part of the development of a new area of rocketry which will contribute to teaching initiatives, and will lead to publishable results in refereed journal and conference papers

Supervision: The project will be supervised by:

- Prof JG Chase (Controls and dynamic modelling)
- Dr CE Hann (Controls and dynamic modelling)
- Assoc Prof XiaoQi Chen (Instrumentation/sensors)
- Dr. M Jermy (Aerodynamics)
- Dr D Aitchison (Product Development)
- K Adams (Industry Mentor)