Project Proposal

Ground Station and Tracking System for Western's CubeSat

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Statement of Problem

A CubeSat is a miniature satellite intended for low earth orbit (LEO), measuring some multiple of 10x10x10 cm and weighing less than 1.33 kg in mass [1]. Western University has received a grant from the Canadian Space Agency's (CSA) Canadian CubeSat Project (CCP) to design and build a 2-unit CubeSat, to be launched after 2021.

An important aspect of the CCP is a ground station and satellite tracking system, with main objectives of aligning an antenna towards the CubeSat as it flies overhead and achieving telecommunication link regardless of the geographical location of the station, if the satellite is passing within the station's field of communication. Other main objectives of the ground station are to provide real-time communication with the satellites, monitor and predict the movement of the satellite, and communicate with other systems control the satellite and its critical infrastructure [2]. The Western CubeSat team will be designing two complete CubeSats and its systems, one named Opportunity that communicates using ultra high frequency (UHF) and the other named Spirit that communicates using S-band, that will undergo a trade-off at the end of the year. However, the ground station must be robust to either communications schemes. As of now, there are only plans to launch one of the two units, but the ground station must be able to track CubeSats from other organizations part of the CCP.

With regards to ground stations, there are some constraints and common issues. A functional constraint is that the ground station needs to accurately predict the satellite's orbit using parameters relating to its trajectory. Another constraint is that though the antenna should be able to detect any satellites in LEO, it needs to be able to detect the CubeSat if it is in the field of vision. The entire CubeSat project has a budget of $200,000, but the cost constraint for the ground station is $1000. Environmental constraints include motor function in fluctuating weather and temperatures. Any societal, ethical, legal, and health and safety requirements have already been considered by CSA prior to launching the CCP. There are certain codes with CSA and other space agencies that need to be followed when communicating with the satellite.

Background Information

UHF and S-band Communication:

One of the two CubeSat designs will communicate using UHF. UHF represents radio frequencies near 300 MHz, with waves that travel by line-of-sight propagation (directly from source to receiver) or ground reflection. UHF wavelengths are usually quite short, allowing for high gain antennas to be quite small and lightweight [3]. The second CubeSat design will use S-band communication, which represents microwave frequencies nearing 2 GHz. This frequency band also uses short waves, allowing for high gains, and is specially optimized for two-way communication between the satellite and the ground station [4].

Antennas:

There are many types of antennas for satellite ground stations, with varying requirements including operating frequency, directional gain, and bandwidth. The CCP will consider two types of antennae to be used; the Yagi-Uda array and Parabolic dish antennas. The Yagi antenna, in Figure 1 below, is one of the most common antennae designs because of its simplicity and high gain. It is a travelling wave antenna with an operating frequency range of around 30 MHz to 3GHz, which encompasses VHF and UHF bands [5].

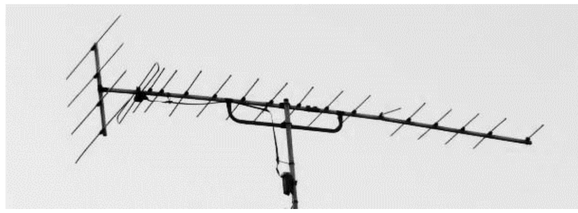

Figure 1: Yagi-Uda antenna

Since Yagi antennas are so well known and analyzed, the design process for each specific application is based on a series of industry standard design parameters. Overall, some advantages of the Yagi-Uda antenna are its high gain and directivity, ease of maintenance, and broad coverage of frequencies. It can also be quite small and portable. Some disadvantages are that it is prone to noise and atmospheric effects [5]. Arguably an even more well-known antenna is the parabolic reflector/dish antenna. These antennas also have a high gain and usually operate between 2 to 28 GHz, suitable for S-band communication [5]. The typical structure of a dish antenna can be seen in Figure 2 below.

Figure 2: Parabolic reflector/dish antenna

This structure consists of a feed antenna pointed towards a giant parabolic reflector dish. The larger the dish, the higher the gain. A main advantage of the parabolic reflector antenna is its high directivity as power is only required over a small area and the ability to angle the antenna allows for the separation of satellites using the same frequency band. Some disadvantages are that this is a costlier antenna and depending on the gain required, the size can get quite large [5].

Mechanical Construction:

The antennae's base needs to be securely attached to the ground so that it does not move. Therefore, it requires a heavy base to have a low center of mass when assembled. This will also aid in the accurate positioning of the antenna as environmental factors would not alter its positioning. The rotator must be mounted on the base securely to prevent vibrations from the motors and the moment of the antenna from altering the positioning. Furthermore, the wiring for the rotator needs to have enough slack to allow the motors to rotate fully.

Keplerian Orbital Mechanics:

One formula that predicts the movements of a satellite with respect to a rotating celestial body is the Keplerian Orbital Elements (KOE), seen in Figure 3. KOE takes into consideration that all orbits are elliptical in nature and thus have a major and minor axis [6]. Additionally, the model considers four angles referring to the rotation of the orbit and two parameters defining the shape and size of the orbit. With these parameters, a unique orbit can be described, and by making assumptions that the elements either will not change or will change in a predictable way (e.g. the semi-major axis decreases due to orbital decay) then an accurate predictive model can be developed [6].

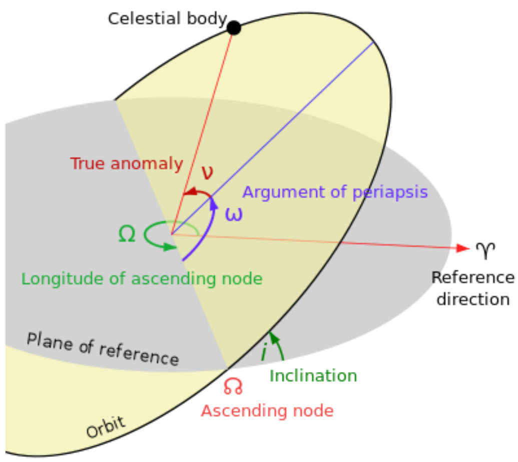

Figure 3: Keplerian orbital elements

Simplified General Perturbations Orbital Model:

Direct modeling of the orbit is generally not possible due to the precision required to model every deviation from the regular path that is caused by an external influence, known as perturbations. Simplified General Perturbations (SGP) models are used to model the orbit of LEO objects. The two-line element set is a data format that encodes the orbital elements of a satellite at a given point in time. The two-line elements that are created from the SGP orbit determination can be used to model an adequately accurate propagation of the CubeSats motion [7]. The limitation of the SGP model is that the propagation calculated can only be guaranteed for a couple of days. Therefore, the model will have to be updated with the new data collected from each passing of the CubeSat.

Geo-Tracking:

An objective for the ground station is to be portable. To accomplish this, the position of the antenna relative to the satellite needs to be considered in the orbital model of the satellite. When the antenna is moved, the positioning of the antenna needs to be calibrated to adjust for the change in relative position. This can be done by tracking the longitude, latitude, and height above sea level of the antenna using a GPS. The calibration involves tracking the sun and adjusting the antenna's elevation and azimuth to reflect the change in location [8]. The control loop that calibrates the antenna depending on the strength of the signal received will fine tune the calibration.

Rotator Control:

In the ground station, there are two motors to control the position of the antenna and thus, a rotator controller is necessary to supply specific current and voltage to the motor, control forward or reverse rotation, and regulate the speed and torque of the motor. Motor controllers and motor drivers can both achieve this task. Motor controllers use digital communication that allows for feedback such as measurements and error detection [9]. A motor driver simply handles the power to drive the motors, and digital control must be done by an external microprocessor [9].

Radio Transceiver (Telecommunications):

A transceiver is a device comprising both a transmitter and a receiver that are combined and share common circuitry or a single housing. For a satellite, transmission and reception may work at the same time, which requires the transmitter and receiver to operate on different frequencies, so the signals do not interfere with each other. Satellite communication networks often employ a full-duplex transceivers mode, meaning both parties can communicate with each other simultaneously. To prevent interference caused by multiple sites transmitting on the same frequencies, government agencies and standards organizations around the globe try to keep the usage organized and often such controls take the form of government regulations which carry the weight of law [10].

Project Objectives and Scope

The goal of this project is to design and build a functional satellite tracking station with high alignment accuracy between Western's CubeSat in orbit and the ground station itself, to achieve better communication and data transfer. The main objectives of the ground station are that it must:

- Be able to physically align itself with the CubeSat
- Be able to geo-locate itself
- Monitor and predict an orbital trajectory to track
- Correct antenna direction if communication is not established
- Be resistant to the effects of the external environment

The scope of this project will cover the orbital prediction algorithm that the ground station will employ to track the satellites' orbits, the elevation and horizontal alignment (known as altitude and azimuth angles respectively), the control system for mitigating tracking error, and finally, the electrical and mechanical subsystems for motor actuation and sensory data acquisition. Communication between the CubeSat and the operations team will not be covered in this project's scope, and neither will the design of the antennae that will be mounted on the tracking station. Resources that are available to us for this project include contacts in the CSA CPP technical support who have experience in ground station design, open source projects based on CubeSat tracking and communication, scientific reports detailing the concepts of satellite motion in LEO and how to model these orbits, and an interdisciplinary team with working knowledge of various aspects of the CubeSat mission parameters.

Methods (Plan of Action)

Antenna Consideration:

Though antenna selection is outside of the scope of this specific project, the mounting and placement of the selected antennae are essential to the design of the ground station, which must be able to track multiple CubeSats with a single ground station. Of the two satellite designs, one will operate in the S-band and the other will operate in the UHF band, so the ground station must be able to work at these two frequencies. Since the two antennas being considered can only operate in one band or the other, this ground station will need to incorporate both the Yagi and parabolic dish types of antennas.

One possible solution is to make the ground station and antennae modular so that the antennas can be switched out. Though this is the simplest solution, it is not ideal as it would not be able to track satellites of differing communication bands at the same time. This would also require more maintenance and human interaction, as someone would need to physically switch out the antenna on the ground station, which is usually in a remote and rarely visited site. A similar solution would be to have two identical ground stations with a different antenna, though that would heavily increase costs. The last solution would be to mount both types of antennae on the ground station and have each one track only one type of satellite without having them interfere with each other. Since they operate in different frequency bands, the presence of one satellite will not affect the other in terms of actual communication and tracking. However, the physical movements of each antenna need to be considered, so they will not collide. Though this will require more calculations and introduce additional dimensional constraints, this is likely the ideal solution for this specific problem definition.

Project Subsystems:

Given the objectives above, the project has been broken down into three main subsystems that integrate to form a fully functioning ground station. The three subsystems are: the Orbital Prediction Subsystem (OPS), the Angular Alignment Subsystem (AAS), and the Accuracy Control Subsystem (ACS).

How these subsystems work is that the OPS will be given telemetric data from the CubeSat via radio communication (again, the reception of the data outside the scope of our project, it is implied that we will be able to receive the data) during the time that it passes over the ground station. The OPS will then use the data to predict how the CubeSat will move during the time that it is not “visible” to the ground station so that it can track the satellite during its next pass. The OPS will then relate the predicted trajectory of the CubeSat to the required azimuth and altitude of the antennae to achieve the strongest connection. These azimuth and altitude angles are encoded to some digital signal that will control actuators in the AAS to physically position the antennae in the direction of the CubeSat. The ACS works in tandem with rotary sensors, which measure the actual azimuth and altitude of the ground station and compares it to the desired angle as determined by the OPS. Should there be error greater than the rotational resolution of the actuator, then a corrective signal is sent to the motor to ensure accurate pointing. Collectively these three subsystems should result in the functional operation of the ground station.

Preliminary Concepts and Evaluation:

Looking at the three subsystems in more depth, we can further expand on the acceptable solutions for this project. Regarding the Orbital Prediction Subsystem, some viable solutions that are being researched include Keplerian Orbital Parameters and Two-Line Elements to model the trajectory as a function of rotation, velocity, eccentricity, and the remaining Keplerian Elements. Another solution would be to have a GPS mounted to the CubeSat and have its past coordinate data be used as sample points for developing a regression curve that will indicate the future position of the specific CubeSat. The advantage of the GPS solution is that it is highly accurate and robust, and it is easy to correct any errors in the model as the exact, correct position of the CubeSat can be obtained during the subsequent pass [11]. Additionally, an algorithm for predicting future location based on coordinate data and polynomial regression is computationally inexpensive if the data is managed well. However, where this proposed solution falls short is in the implementation on the CubeSat itself. The introduction of a GPS on the satellite will reduce the amount of volume, mass, energy, and transmission bandwidth available for more critical components. For this reason, it is proposed that the solution employed simply requires components installed to the ground station as there is more leniency in terms of constraints.

From this, a functional solution would be to design a predictive algorithm based on the Keplerian model of satellites orbiting a body. This model takes into consideration the direction of the satellite, as well as other known parameters such as the angular velocity of the body being orbited by the satellite, to compute where it will be in the future. This method also requires no additional components on the CubeSat itself as a telemetric system will already be in place as part of its payload requirements; however, it will be subject to error should the satellite stray from its orbit due to any unexpected events.

The next subsystem would be the Angular Alignment Subsystem. The concept of antennae pointing to satellites is a well documented and exact science, so the solution of aligning the antennae is to simply have two motors driving two rotary joints to control the position. Where this solution requires some thought is when considering what actuators are viable for this task and using the actuation system to counteract negative operating conditions brought on by environmental. The common solution is to employ either stepper or servo motors to rotate each joint so that they align with their target. Servo motors provide high angular resolution, have a fast response time, and are controlled using pulse width modulation (PWM), making them an excellent for applications where speed and precision are required [12]. This is offset by the poor torque supplied, meaning that in applications where they are required to drive some object they will simply fail, which is the case for this application. The alternate, stepper motors, have a very similar characteristic where they respond quickly; however, they respond to an applied voltage rather than a PWM signal, eliminating the need for a signal generator [13]. The main advantage is that stepper motors produce significantly more torque than servos, making them a more suitable actuator for the application of positioning an antenna. In terms of conditions imposed on the CubeSat by the environment, the main factors are precipitation such as rain and snow, and temperature fluctuations due to geographic location and seasonal temperature changes. This imparts a new criterion for the motors selected as they need to be able to operate in temperatures between $\pm$ 30℃ and with some precipitation present. Also, by leveraging the motors, specifically the motor that controls the altitude, the antennae can be pointed down to remove built up snow or rain water that has collected (in the case of a parabolic dish).

The final subsystem is the Accuracy Control Subsystem, which largely ties in with the AAS. This subsystem again falls under a very well defined and understood phenomena whereby the accuracy of the tracking system can be increased by mitigating error, and therefore, a solution can be found by determining how the error will be detected and what control architecture can be implemented to effectively eliminate it. To detect the error, a sensor would be needed to compare the actual physical rotation of the antennae to the desired rotation as determined by the OPS. The ideal sensor would decrease latency and rise time and increase resolution. An incremental encoder, a high-resolution potentiometer or a rotatory magnetic Hall sensor can be used to determine the angular position of the tracking station [14]. All three sensors provide very similar effects, except for the potentiometer, which is physically limited to a set range of values. It is difficult to say objectively which sensor will be most effective in this application without applying objective selection methods, so the solution space for angular detection is very broad. In terms of control architecture, any closed control loop where the angular error is affected by some stable transfer function that yields no steady state error is a valid solution for this subsystem.

Plan of Action and Methods:

The table below summarizes the previously outlined subsystems and other major work within the project. Also summarized are the specific tasks and methods that will be used to complete these tasks.

Table 1: Project progression with required tasks and methods

	Tasks	**Methods**
Background Research	Research the following related topics: types of antennas, tracking multiple satellites, types of communication, orbital model, location and geo-tracking, rotators for alignment, mechanical construction, radio transceivers, control, software, and costs.	Look into scholarly articles and past projects.
Antenna Selection	Determine which type(s) of antennae are viable.	Mathematical modelling and analysis using MATLAB antenna toolboxes, geometric analysis including mass, moment, size, and shape factors.

Angular Alignment Subsystem	This includes motors, geartrain, mounting, and weatherproofing.	Speed and torque analyses, motor selection, geartrain design using Shigley and American Gear Manufacturers Association standards, FEA (stress and strain analyses), CAD modelling, simulation.
Accuracy Control Subsystem	This includes sensors, control architecture, and electrical components.	Sensor selection, feedback loop, and gains, mathematical modelling and Simulink simulations, controller design (root locus analysis), PCB design using Eagle, microcontroller programming, and wiring.
Orbital Prediction Subsystem	This is the orbital prediction model software.	Visual Studio, optimization strategies, data structures and algorithms, MATLAB simulations, and manual numerical analyses.
Prototype and Testing	Integrate subsystems and develop a working prototype. Test extensively.	Prototype construction, testing using already orbiting CubeSats and other satellites in space.

Project Schedule and Tasks

Higher Level Project Plan:

The overall project progression will follow the engineering design process broken down into the phases in the table below. The design process will be heavily influenced by the course deliverables, which are also specified in the table with their respective due dates.

Table 2: Major project phases and overall timeline

	Task	**Related Deliverable**
Problem Definition	Select a project that includes all elements of mechatronic systems engineering including mechanical engineering, control, and software engineering. Develop a design problem and description.	Project Selection, due September 20th, 2018
Background Info and Research	Provide context to the problem. Research what is already on the market and what has already been done by others.	Design Proposal, due October 5th, 2018
Specify Requirements	Identify project supervisor needs, design specifications, and design constraints.	Design Proposal, due October 5th, 2018
Ideate, Evaluate, and Select Solution	Discuss possible solutions to the problem while considering the project objectives and constraints.	Phase I Report, due November 15th, 2018

Design Phase	Complete design of the solutions mechanical, electrical, software, and control subsystems.	Design Review 1 on October 31st, 2018 and Design Review 2 on January 16th, 2019
Prototype and Test Solution	Construct a working prototype with integrated subsystems.	Showcase Presentation on April 3rd, 2019
Revisit Requirements	Ensure that the solution and working prototype satisfy all the objectives and constraints outlined at the beginning of the design process.	Final Report, due April 11th, 2018

Detailed Project Plan:

These major project phases can be broken down into more tasks that are specific to the project. These tasks along with their project start dates, end dates, and hours required are in Table 3 below. This is also illustrated using a Gantt chart, which can be seen in Appendix 1.

Table 3: Detailed project task list, dates, and time allocation for the group

Task	Start Date	End Date	Hours
Problem Definition	2018-09-17	2018-09-20	2
Outline Objectives & Constraints	2018-09-17	2018-09-20	2
Project Selection	2018-09-17	2018-09-20	5
Background Research	2018-09-21	2018-10-03	10
Design Proposal	2018-09-30	2018-10-05	20
Antenna Selection	2018-10-03	2018-10-07	10
Mounting Mechanism	2018-10-15	2018-10-25	15
Motor Selection	2018-10-22	2018-11-05	20
Sensor Selection	2018-10-22	2018-11-05	20
Personal Contributions Report I	2018-10-23	2018-10-25	1
Design Geartrain	2018-10-24	2018-11-01	8
Design Review 1	2018-10-29	2018-10-31	5
Phase 1 Report	2018-11-01	2018-11-15	30
Design Control System	2018-11-03	2018-11-15	20
Preliminary Testing of Subsystems	2018-11-15	2018-11-30	10
Oral Presentation	2018-11-25	2018-11-28	6
Personal Contributions Report II	2018-12-03	2018-12-06	1
Power & Electrical Design	2019-01-07	2019-01-15	8
Power Distribution Circuit	2019-01-10	2019-01-20	6
Design Review 2	2019-01-10	2019-01-16	5
Integrate all Subsystems	2019-01-20	2019-02-15	15
Phase 2 Report	2019-01-30	2019-02-14	30
Prototyping	2019-02-15	2019-03-15	40

Design Analysis & Detailed Design Documentation	2019-03-01	2019-03-14	12
Personal Contributions Report III	2019-03-05	2019-03-07	1
Weatherproofing	2019-03-15	2019-03-30	10
Testing	2019-03-15	2019-04-14	50
Final Report	2019-03-15	2019-04-11	45
Reflection	2019-04-25	2019-04-29	2
		Total	409

Contingency Plan:

It is easily recognized that as the project progresses, it may not follow this outlined schedule. To keep the project on track, all group members will review each others' progress according to this schedule at the weekly group meetings. Changes and adjustments to the phase periods and hours allotted will be made at these meetings. The plan is to spend most of October and November finishing the design of all the subsystems, with the intent of ordering parts in December to be received sometime in January, to be able to begin prototyping. The biggest risk revolves around the fact that this project is interdisciplinary and involves several other capstone teams, whose data and results are relevant to certain decisions in the scope of this project. Weekly meetings occur between all teams to ensure all projects are on track and the use of Slack will be highly leveraged to stay in constant contact with each team's progress.

Resources and Budget

The course allocates a budget of $75 per person, totalling $300 for a group of four. There is also a budget of $100 of free FDM for rapid prototyping from the Electronics shop. In terms of additional supervisor funding, there is roughly $1000 available for the ground station, with the overall Western CubeSat Project having a budget of $200,000.

The budget for other resources can be found in Table 4 below. In terms of engineering hours, if each group member spends 10 hours each week over the 22-week project (not including reading weeks, winter break, or exam periods), there are approximately 880 hours of time available. This table may not include all costs and resources but will be updated as more costs arise.

Table 4: Costs associated with project resources

Resource	Rate	Estimated Cost
Engineering Time	880 hours at $50/hour	$44,000
Actuator Costs	Robust motors 2x$300	$600
Sensor Costs	Estimate	$250
Electrical Components	Estimate	$100
SolidWorks	Standard license for each member 4x$4000	$16,000
MATLAB & Simulink	Standard license for each member 4x$1000	$4,000

Autodesk EAGLE	Standard license for each member 4x$130	$520
Microsoft Office	Standard license for each member 4x$200	$800
FDM Printing	Provided	$100

Team Qualifications

Paavan Raj – Knowledgeable about flight characteristics and trajectory modelling from experience on Western's Aero Design team. Also proficient in numerical analysis, modelling systems on MATLAB, and PCB design.

Annie Wu – Use of a variety of languages for general purpose programming and experience with SolidWorks modelling. Other skills lie with project management, communication, and technical report writing.

Tushar Mahajan – Proficient in CAD modelling and simulation. Also has experience designing electronic systems using iterative design.

Jianhui (Wayne) Li – Experience with drone delivery and control system of Western's Industry 4.0 network and knowledgeable in embedded systems through Raspberry Pi and modelling systems on MATLAB.

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Appendix

Appendix 1: Gantt chart (rotate page to view)