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TETHER SATELLITE SYSTEM DYNAMICS MODELLING

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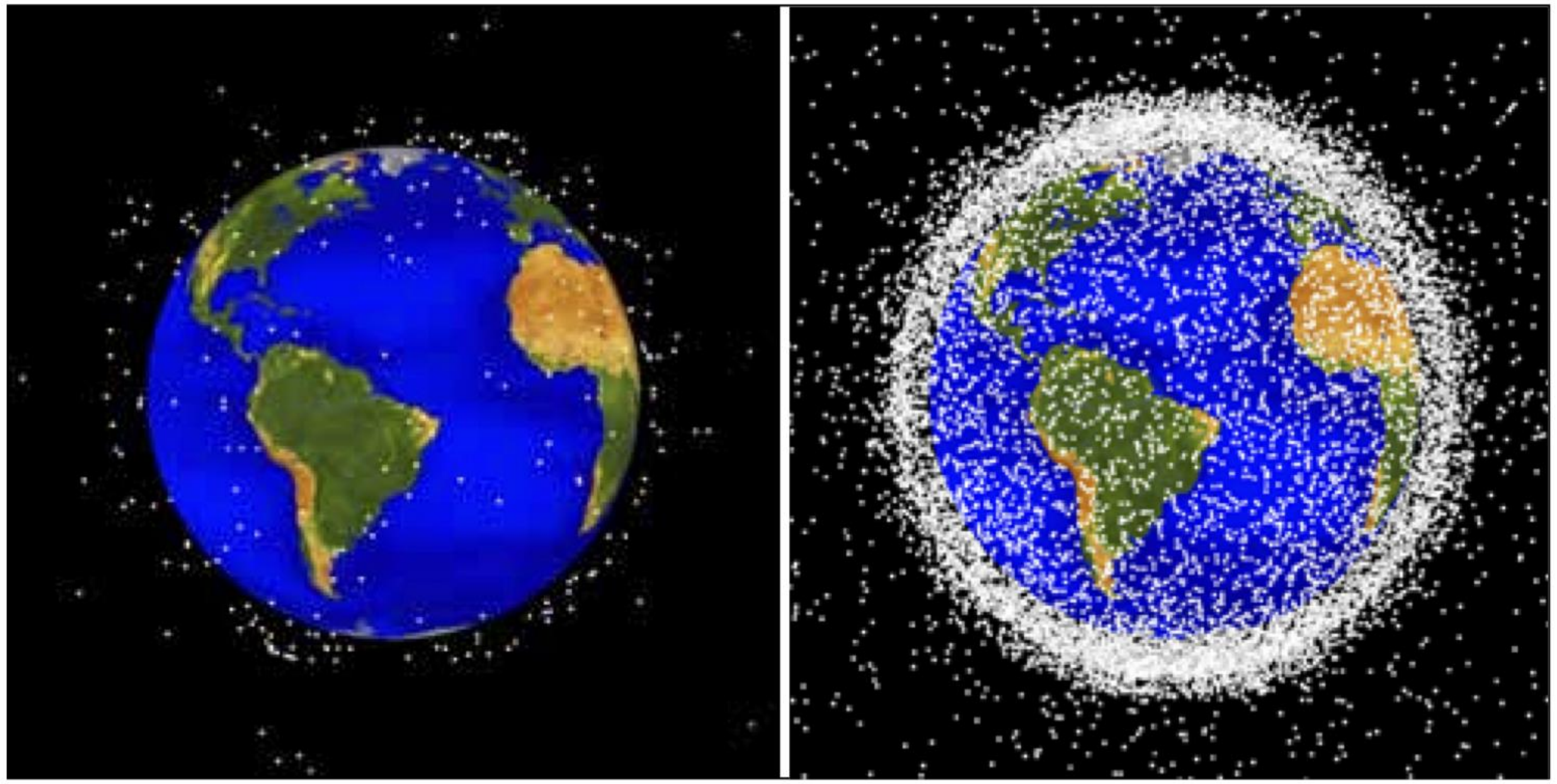
Outline

- Motivation
- Literature Review and Case Study
- Detection using ArduSat Demosat
- Wireless communication Setup
- Testbed fabricating
- Acknowledgement

Motivation

- The Earth is surrounded by tens of thousands of sizeable chunks of debris orbiting at very high speeds
- Add to these larger pieces debris an estimated hundreds of thousands of sub-centimeter-sized artificial particles
- A source for potential disaster—for while these small particles may not seem imposing, they can present a serious threat to functional spacecraft.



Tracked space debris in 1963 and fifty years later in 2013.
Image credit: NASA

Motivation

Debris Kind:

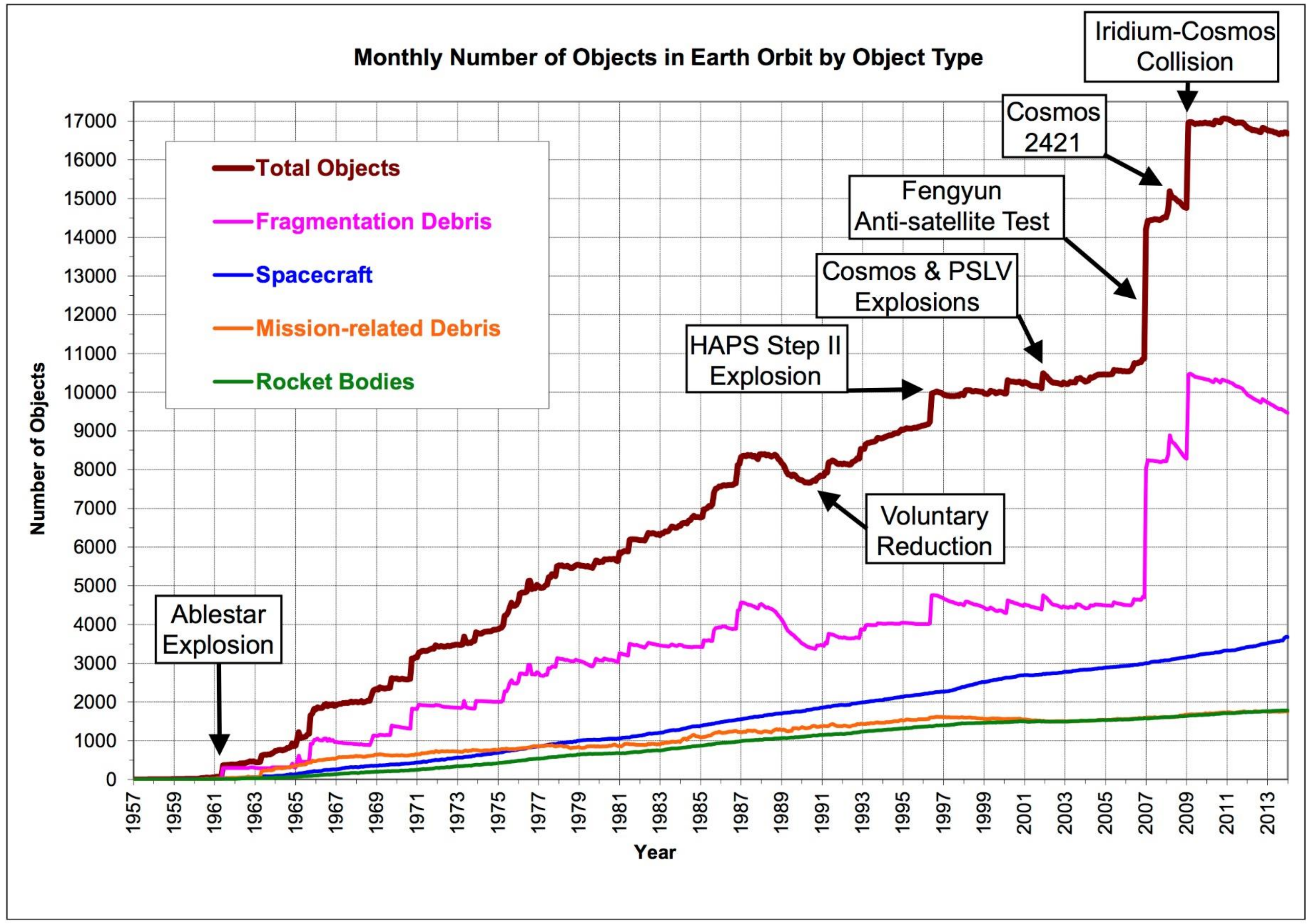
1. Fragmentation Debris
2. Spacecraft
3. Mission-related Debris
4. Rocket Bodies
5. Other sources

"Since 2002 ,The growth(of space debris) has entered into the more feared <u>exponential</u> trend."

——Donald Kessler: former NASA scientist

Debris changing trend over nearly 60 years

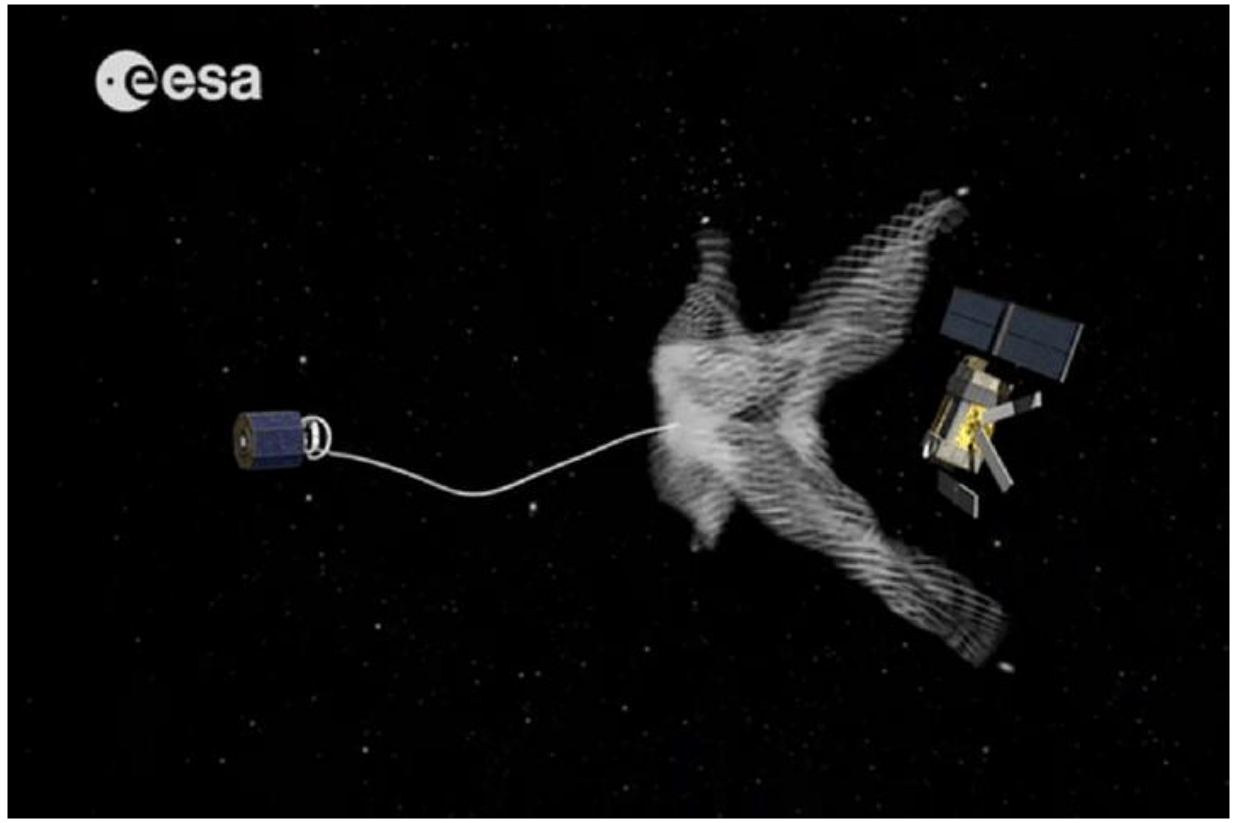
——From 1957 to 2013



Motivation

- Actively Removing Space Debris

Artist's rendition of the JAXA space debris collection mission. Credit: JAXA

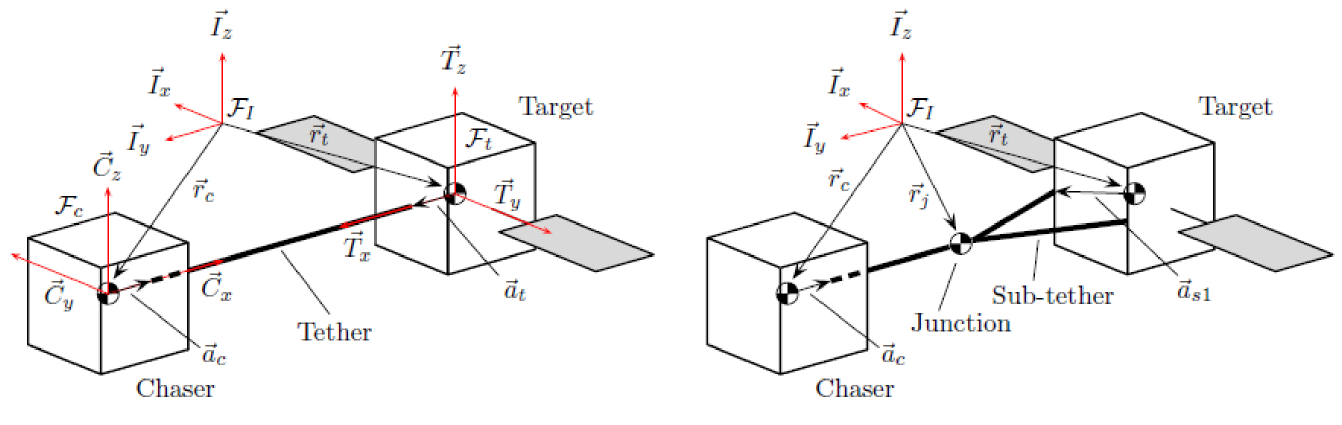


ESA's e.Deorbit space debris collection mission. Credit: ESA

A space debris removal satellite, dubbed Sling-Sat, designed at Texas A&M University.

Literature Review

- Hovell, K., & Ulrich, S. (2017). Experimental Validation for Tethered Capture of Spinning Space Debris. In *AIAA Guidance, Navigation, and Control Conference* (p. 1049).
- Operating state:3-degree freedom of motion, X Y and rotation
- New configuration idea: Sub-tether configuration
- Key physical quantities: Target tether angle ; Target angular rate; Total angular momentum
- Goal: Decrease all the key physical quantities much quicker to make space debris deorbit practically



(a) Single tether configuration with reference frame definition.

(b) Sub-tether configuration. For clarity, $\mathcal{F}_c$, $\mathcal{F}_t$, and $\vec{a}_{s2}$ are omitted.

Literature Review

Assumption

1. Massless tether; constant end-body mass, visco-elastic tether

2. 3 Degree of Freedom, Planar Dynamics, for chaser and target
   - Translational motion along X axis and Y axis, $z = 0$
   - Rotational motion about the Z axis, $w_x = w_y = 0$

3. No external forces applied to the center of mass of the whole tethered satellite system

4. The Inertia matrix is constant and the body frame of each of the end-masses is aligned with the principal axes of the end-masses

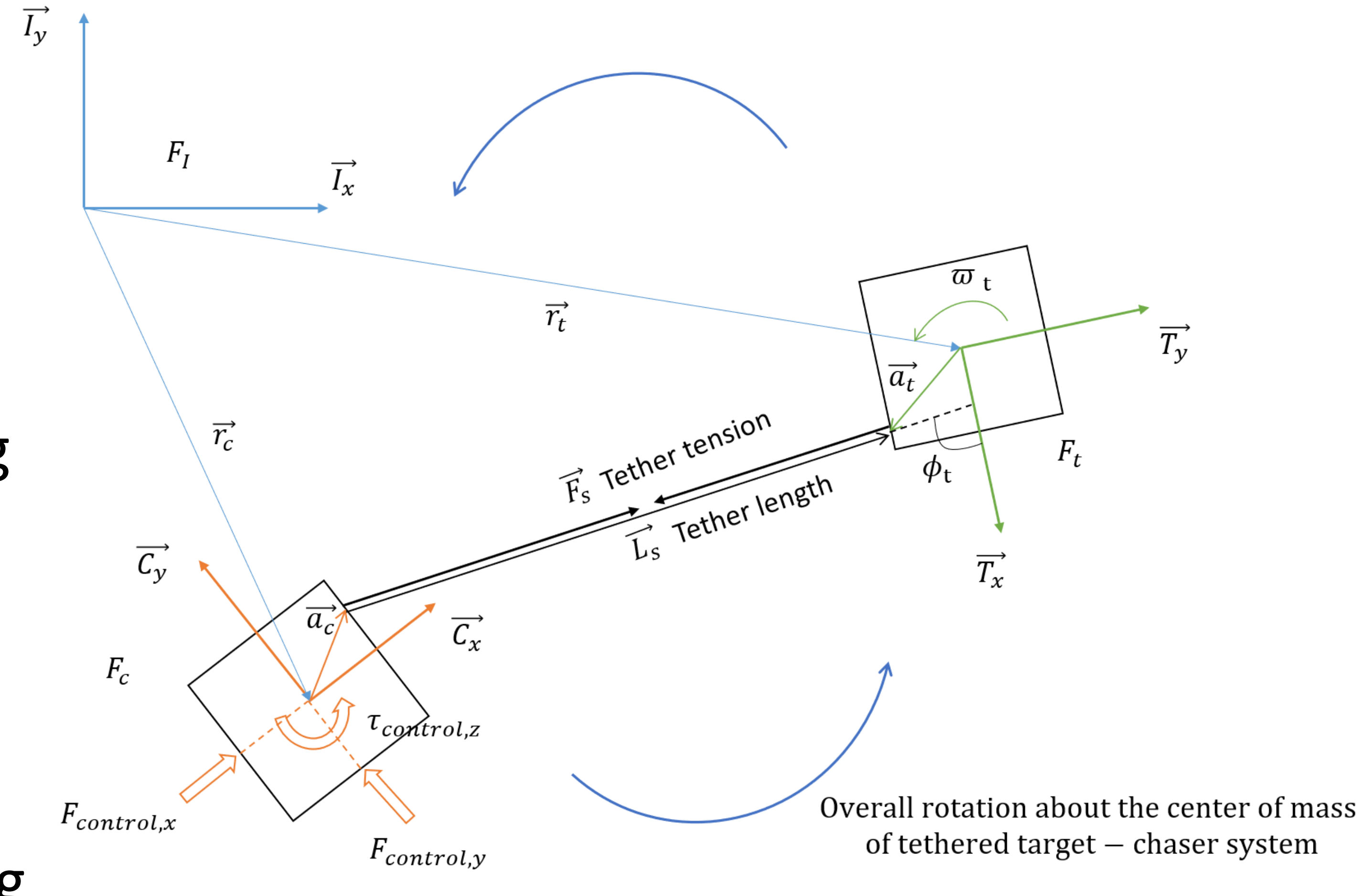
Literature Review

- **Reference frame andCoordinate system**
  - Defined as right-handed system

1. Inertial reference frame F_{I}
   - Reference inertial frame F_{I} Coordinates $\overline{\boldsymbol{I}} = [I_x , I_y , I_z]$
   - Fixed, position of origin point and direction of x , y , z axis don’t change with time

2. Target body-fixed frame F_{T}
   - Reference inertial frame F_{T} Coordinates $\overline{\boldsymbol{T}} = [T_x , T_y , T_z]$
   - Origin point at the center of mass of the target
   - The x axis of target is pointed to the chaser at the beginning

3. Chaser body-fixed frame F_{C}
   - Reference inertial frame F_{C} Coordinates $\overline{\boldsymbol{C}} = [C_x , C_y , C_z]$
   - Origin point at the center of mass of the chaser
   - The x axis of chaser is pointed to the chaser at the beginning



Literature Review

Coordinate transformation

- Attitude matrix $\mathrm{A}(\theta)$: transformation matrix that rotate the vector components from a body frame to Inertial frame

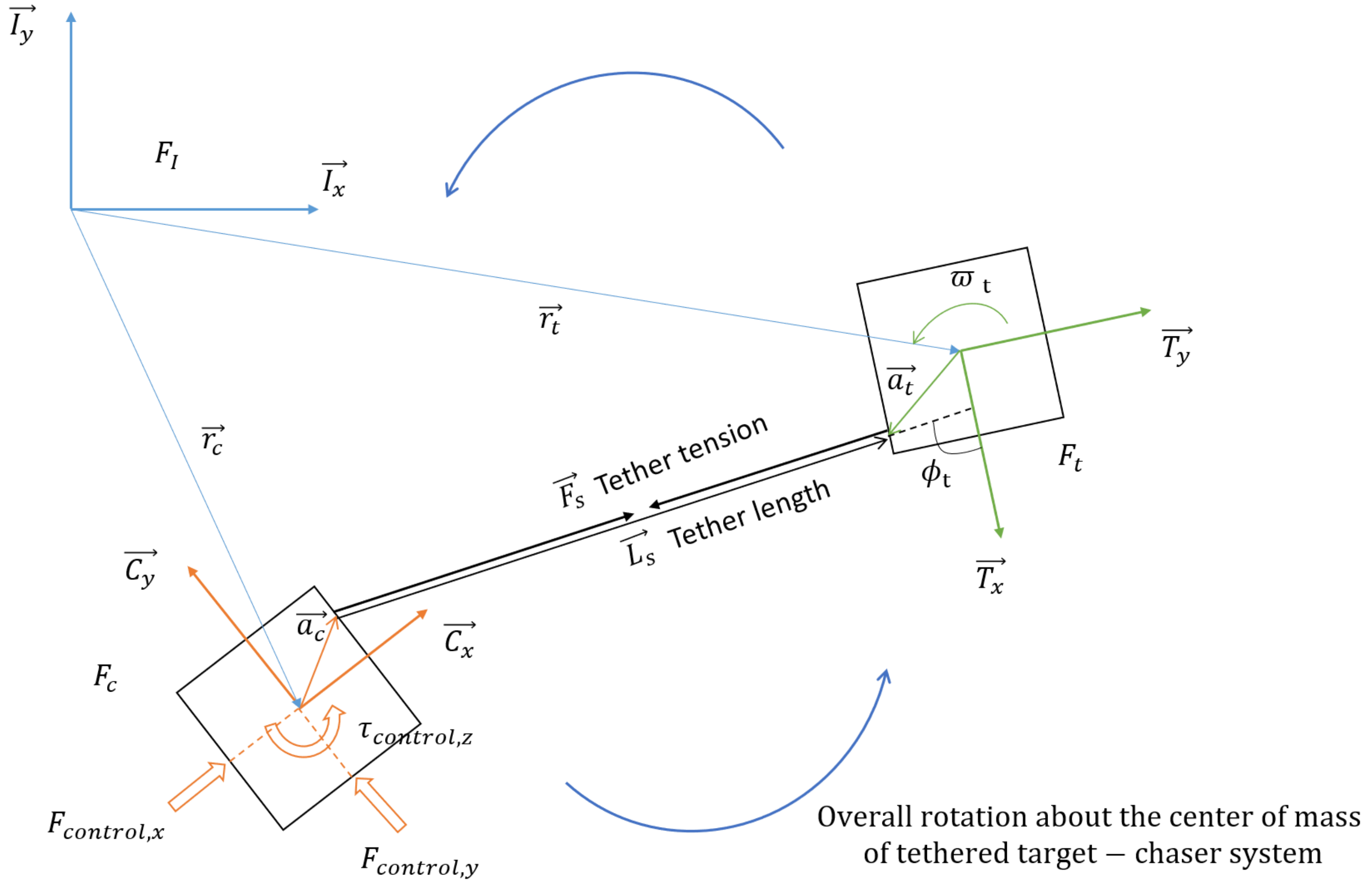
- attitude θ of a body frame is the angle of rotation between the body frame relative to the Inertial frame F_{I} about the z-axis where the z-axis of all inertial and body frames are parallel

$$\mathrm{A}(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}$$

Vectors from Body frame to Inertial frame

$$\mathbf{x_I} = \mathrm{A}(\theta)\mathbf{x_b}$$

$\vec{a}$: Tether attachment vector with respect to the body center of mass, which is fixed in the body frame



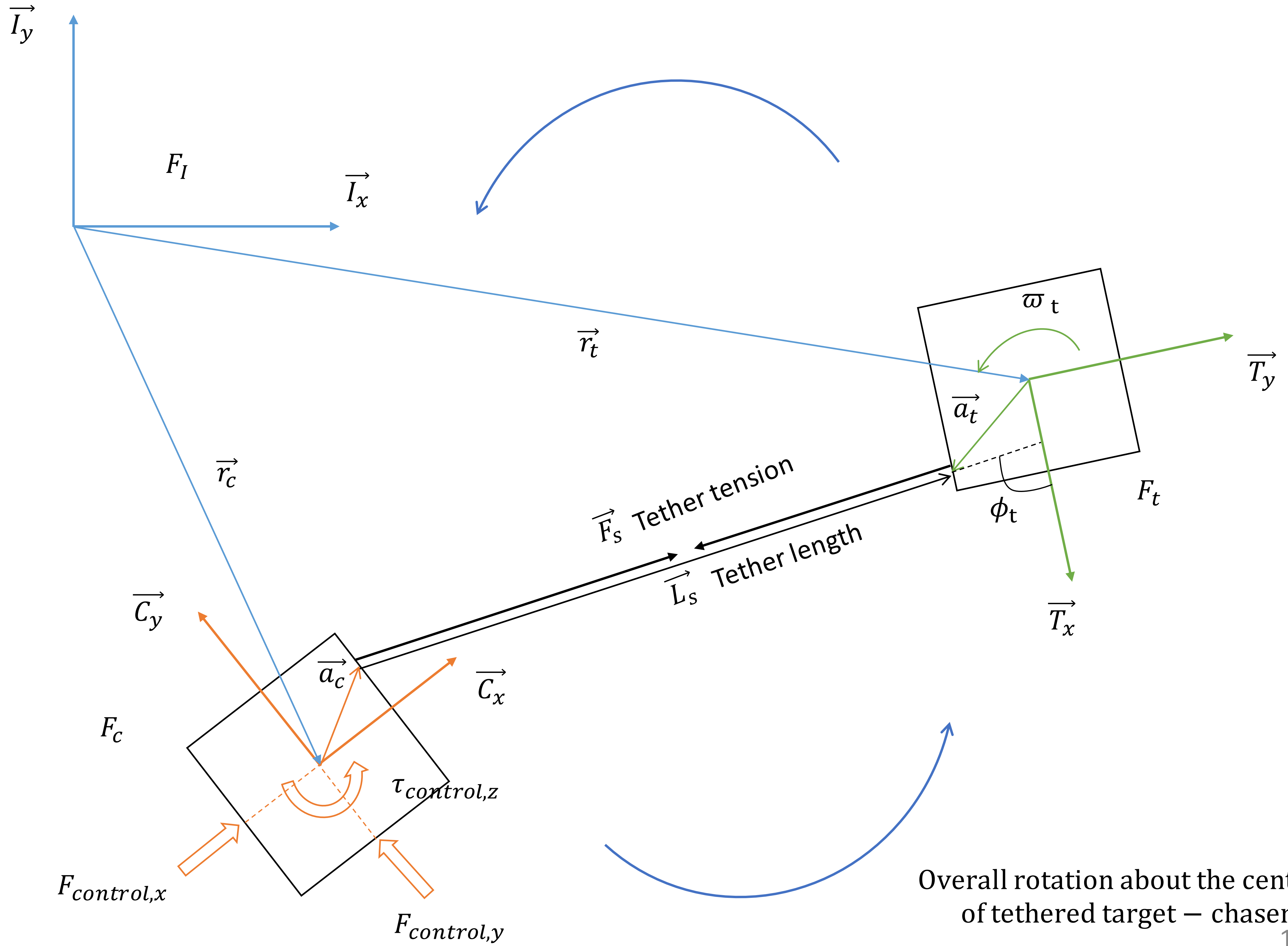
Literature Review

Governing equation: Newton's second law and Euler's equation

- $\mathbf{F} = m\ddot{\mathbf{r}}$ $\quad J_{zz}\dot{\omega} = \tau_z$
- Since reference inertial frame is not rotating around the inertial frame
  - Torque with respect to the inertial frame equals torque with respect to body frame
  - Angular velocity of an end-mass relative to the inertial frame also equals to the angular velocity relative the body frame

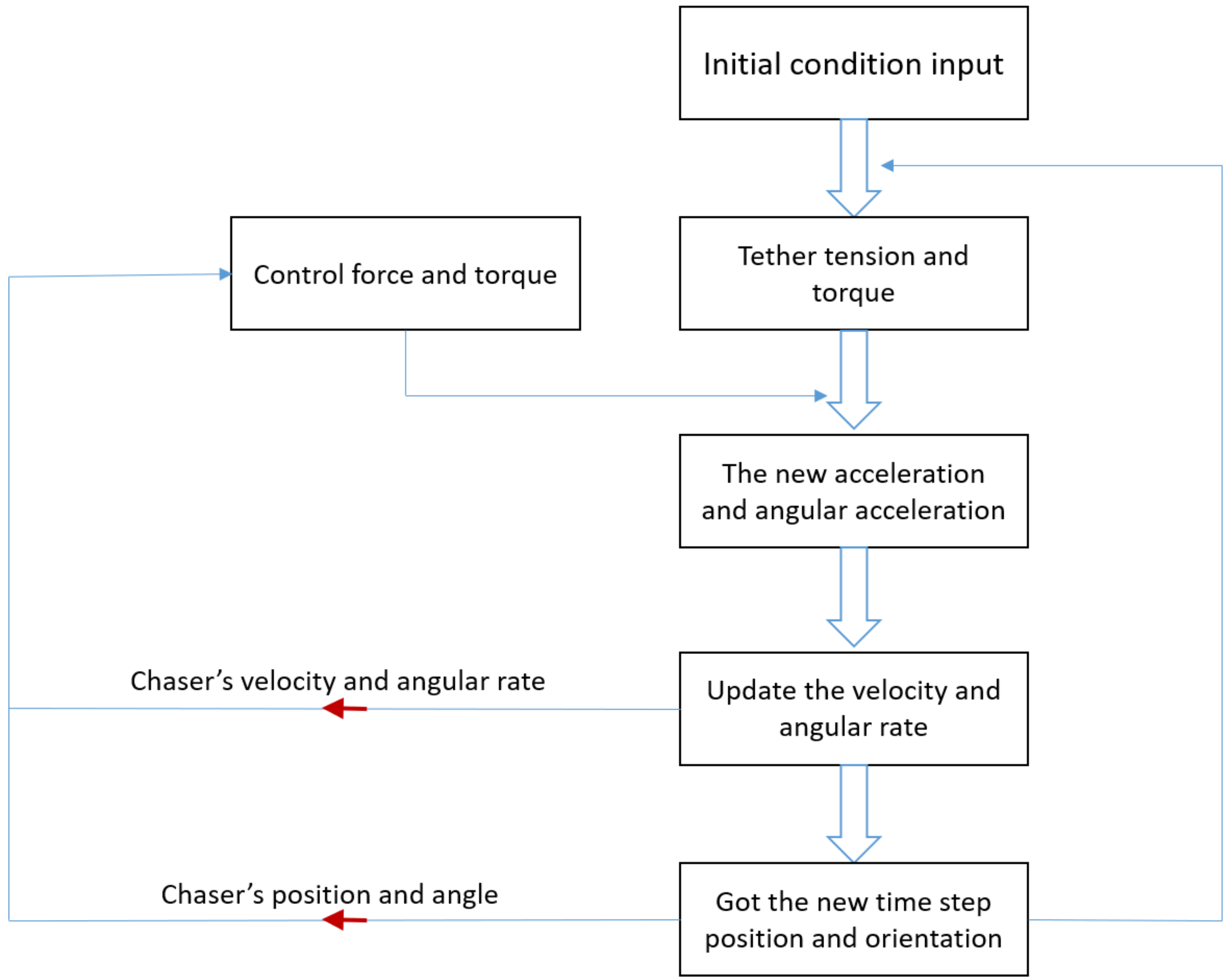
Physics Model for the system

- Nonlinear stiffness, spring damper system
- The damping coefficient of the damper is constant
- Nonlinear spring constant, tether materials : 56% polyester and 44% rubber
  - The spring constant changes as the extension of tether change
  - When tether is extended, the spring force $F_{spring} = k \times (\text{length of stretched tether} - \text{tether natural lenth})$
  - F_{spring}=0 when tether is slacked



Overall rotation about the center of mass of tethered target − chaser system

Literature Review



- **Tether Length**
  - $\overrightarrow{L_s} = -(\vec{r_c} + A(\theta_c)\vec{a_c}) + (\vec{r_t} + A(\theta_t)\vec{a_t})$
- **Tether tension**
  - $\overrightarrow{F_S} = \left(k\left(\left\|\overrightarrow{L_S}\right\| - L_{s,nature}\right) + c\left(\Delta\vec{v} \cdot \frac{\overrightarrow{L_S}}{\left\|\overrightarrow{L_S}\right\|}\right)\right)\frac{\overrightarrow{L_S}}{\left\|\overrightarrow{L_S}\right\|}$
  - Damping force: $c\left(\Delta\vec{v} \cdot \frac{\overrightarrow{L_S}}{\left\|\overrightarrow{L_S}\right\|}\right)$, damping factor multiply the velocity change in the tether's direction
  - $\frac{\overrightarrow{L_S}}{\left\|\overrightarrow{L_S}\right\|}$:Unit vector of tether

Literature Review

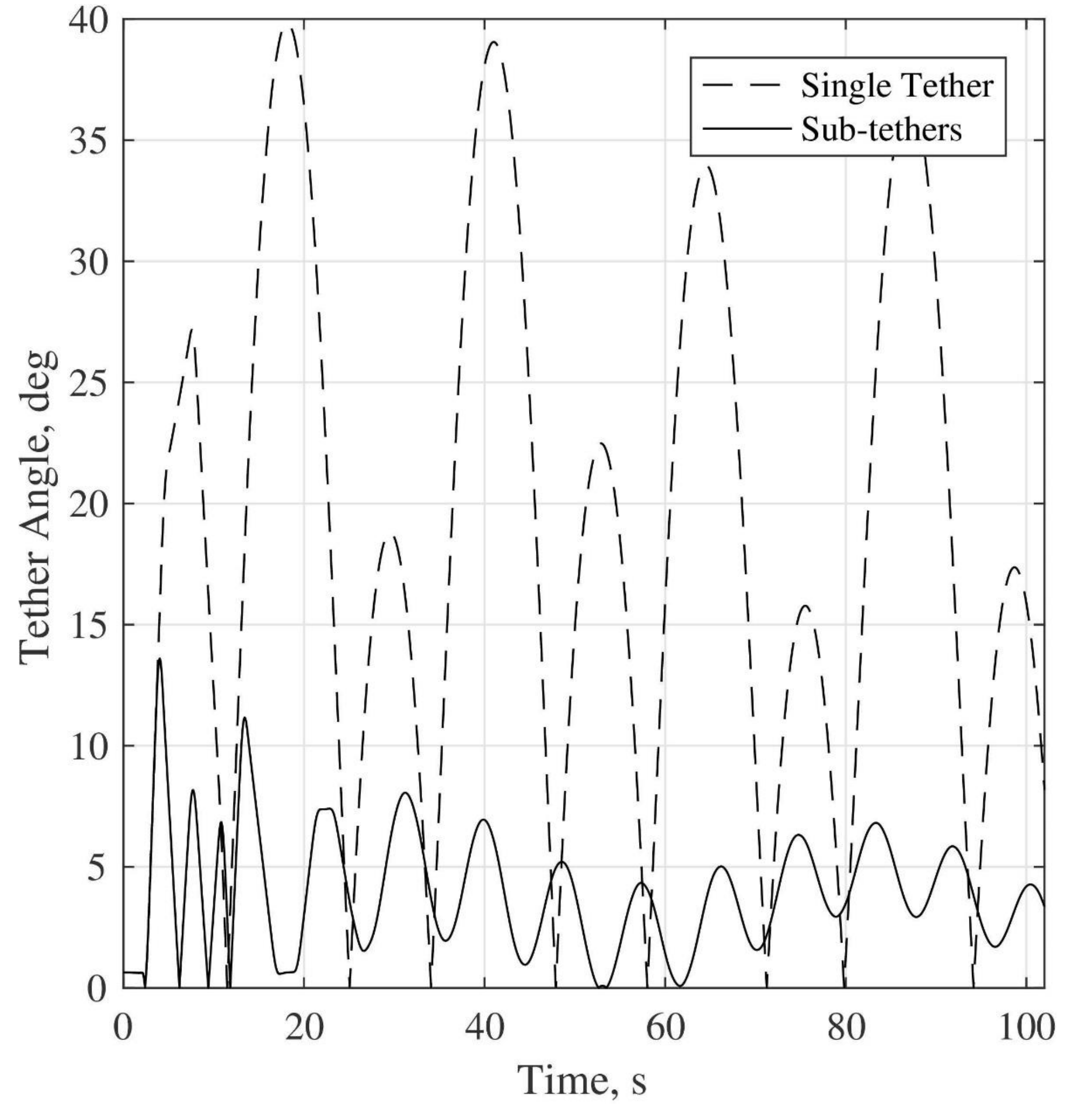
- **Tether torque**
  - $M = \frac{dH}{dt} = \dot{H}_{relative} + \Omega \times H$
  - Ω: the moving frame's absolute angular velocity, doesn't exist in this case(Ω=0)
    - The moving frame just has translational motion in Inertia frame
  - $\Omega \times H = 0$
  - $M = \frac{dH}{dt} = \dot{H}_{relative} = \dot{J_{zz}}\omega = J_{zz}\dot{\omega}$
    - *Torque in inertial frame = Torque in body frame*

- **Euler's equation**
  - $J_i \dot{w}_i + w_i \times J_i w_i = \sum \tau$
  - $J_i = \begin{bmatrix} J_{ixx} & 0 & 0 \\ 0 & J_{iyy} & 0 \\ 0 & 0 & J_{izz} \end{bmatrix}$
  - $w_i = [0 \quad 0 \quad w_{iz}]^T$
  - $J_{izz} \dot{w}_{iz} = \tau_{iz}$
  - $\tau = a_i \times F_S^i$
    - $\tau_t = a_{t,y} F_{s,x}^t - a_{t,x} F_{s,y}^t$
    - $\tau_c = a_{c,y} F_{s,x}^c - a_{c,x} F_{s,y}^c$

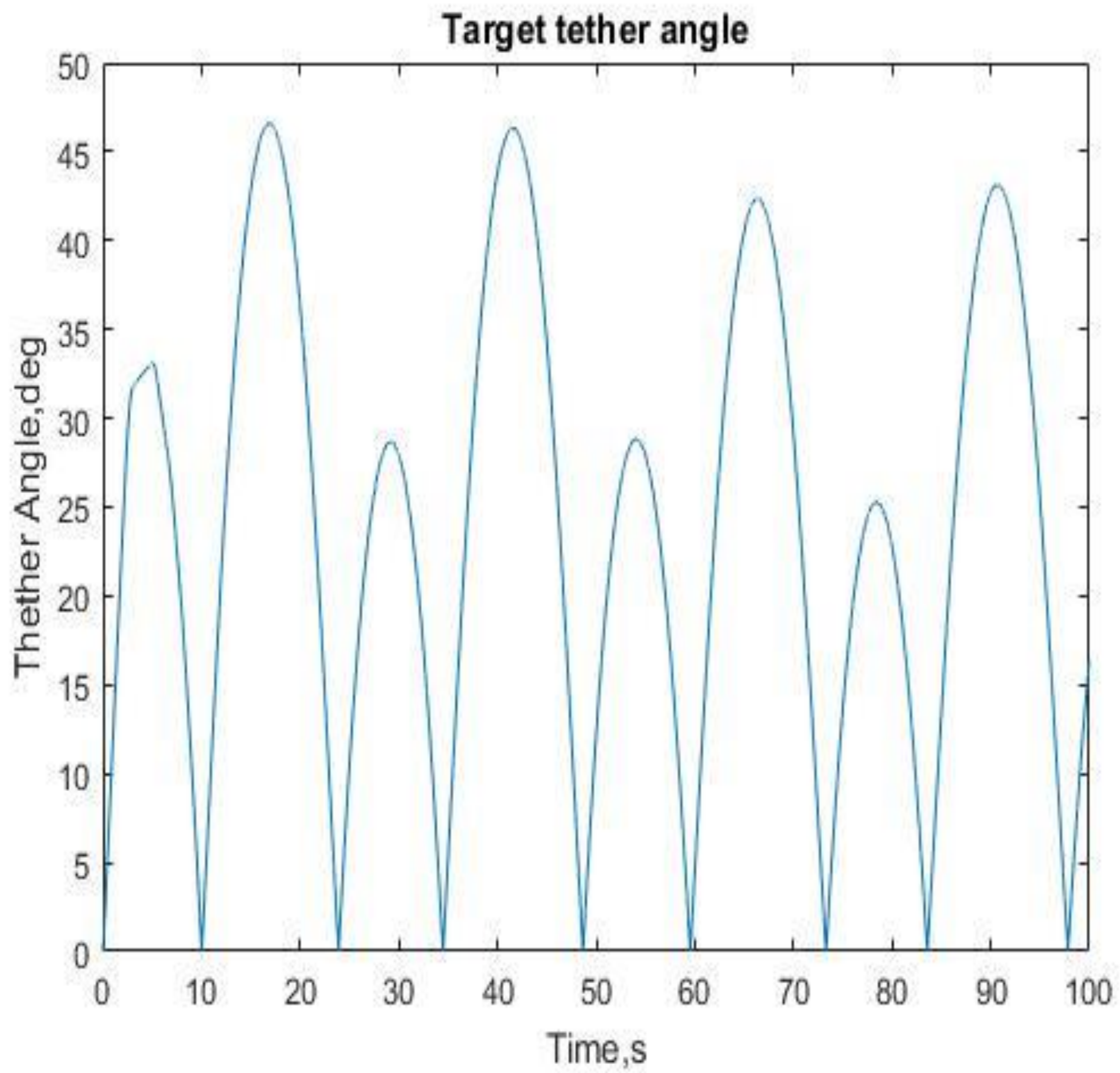
Case study

Hovell and Ulrich (2017) planar single tether thrust stabilization
- Tether angle simulation t = 1-100 s

Kirk Hovell



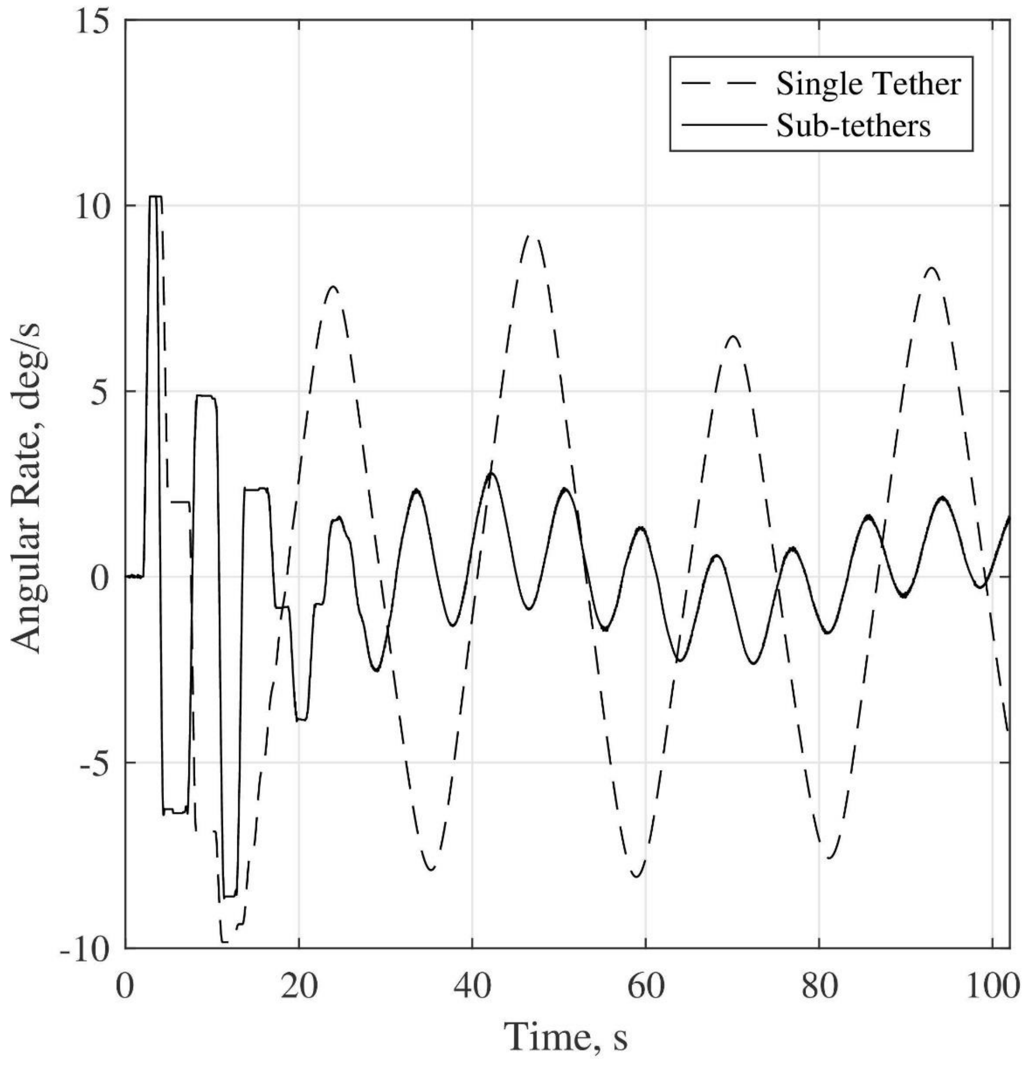
Kaiwen Chen



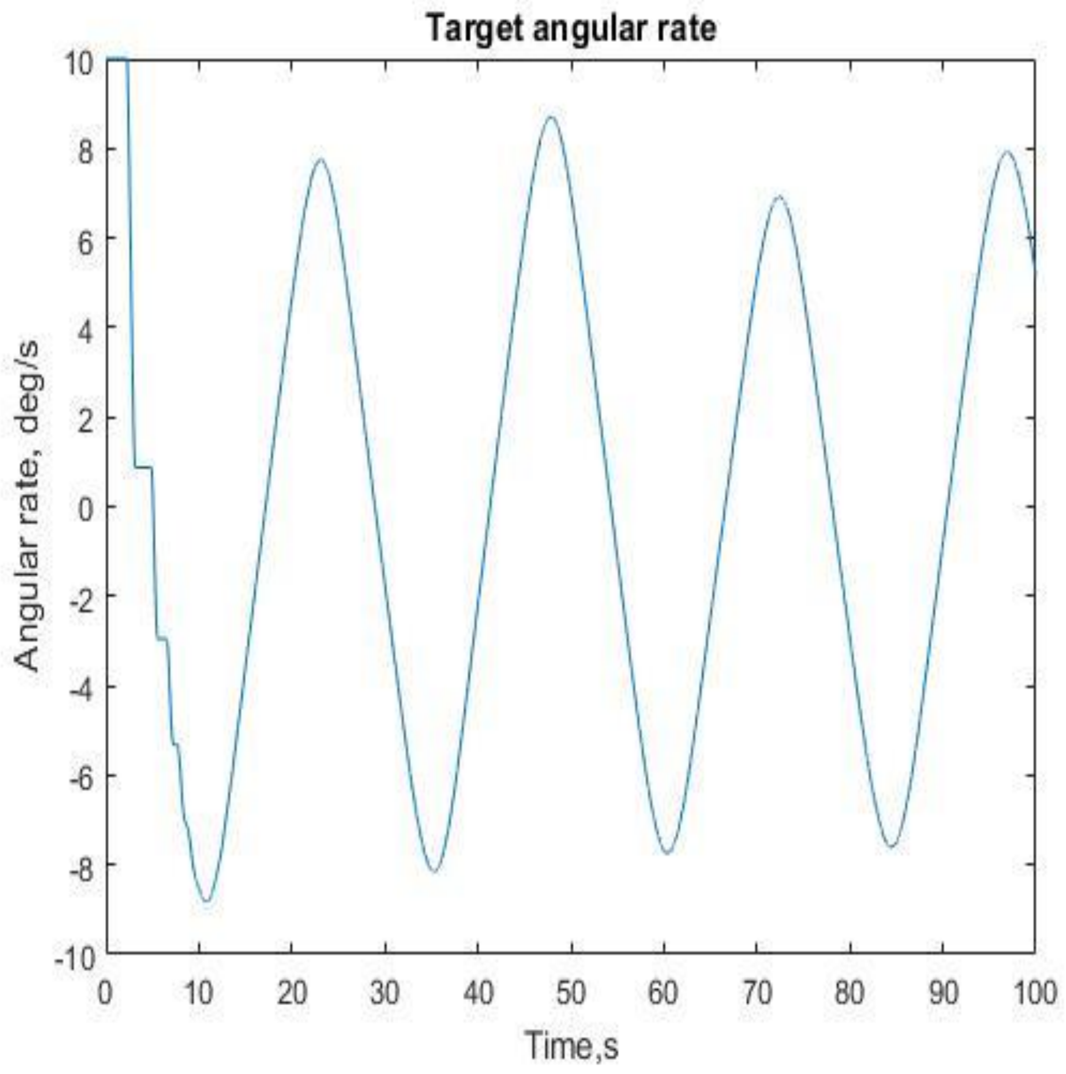
Case study

- Target vehicle angular velocity t = 1-100 s

Kirk Hovell



Kaiwen Chen



Detection using ArduSat

Figure: Ardusat Demosat

Arduino Cubusatellite Standard 1U Demosatellite

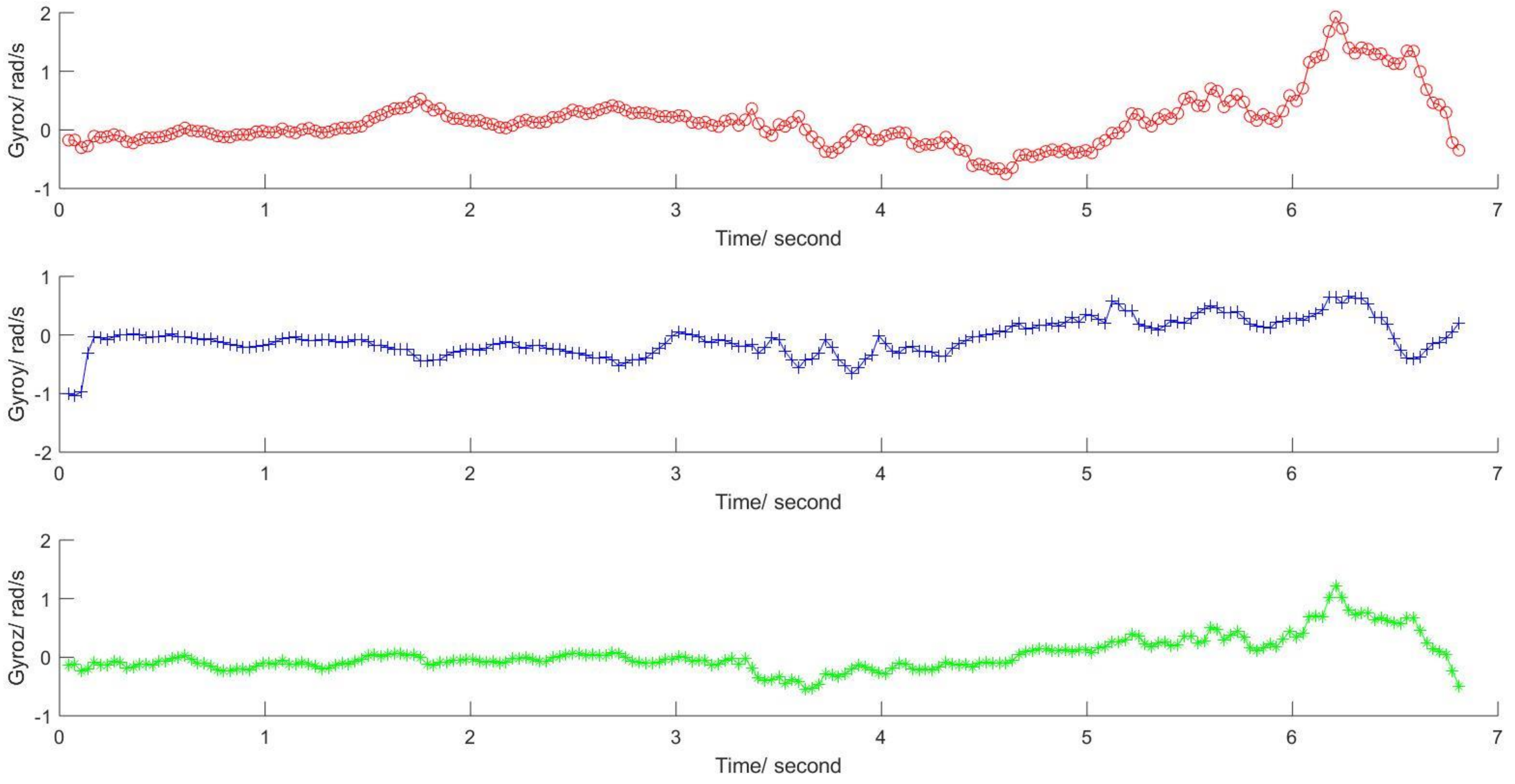
-Sensor board' sensors

- Accelerometer
- Gyroscope
- Magnetometer

Compile the Arduino Board using Arduino ino file

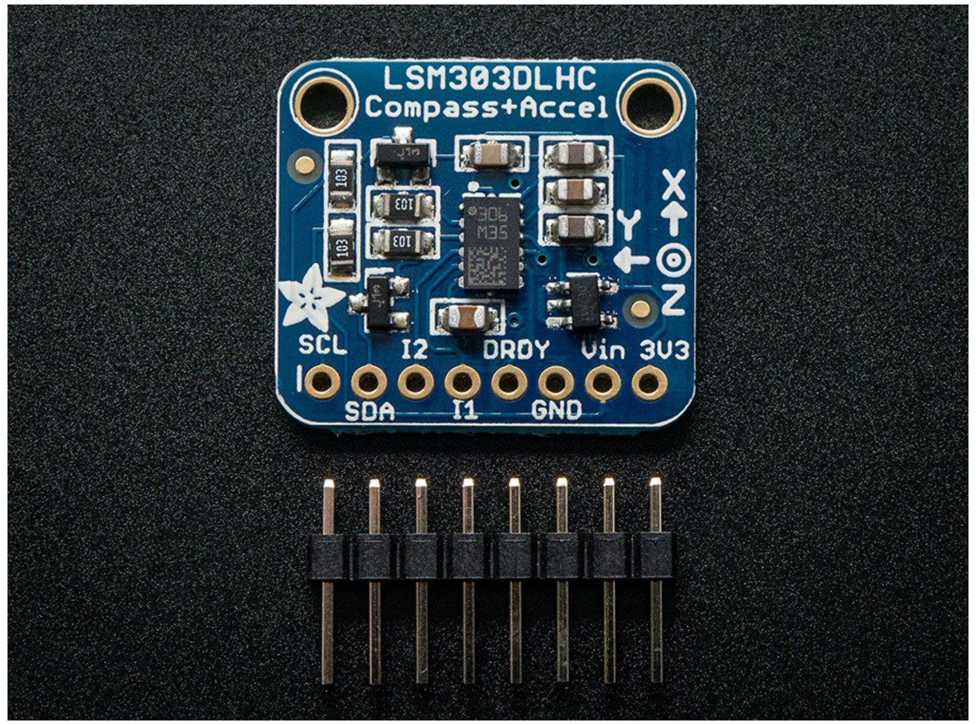
- CSV format: include timestamp
- Highest baud rate 57600 for improving motion-tracking effect
- Individual written MATLAB code for real-time data plotting and recording via USB serial communication

Detection using ArduSat



Update rate: 32HZ

Acceleration: Sensor LSM303 triple-axis accelerometer
Angular rates: Sensor L3GD20 three-axis gyroscope.
Orientation: derived from acceleration and Magnetic intensity



Wireless communication Setup

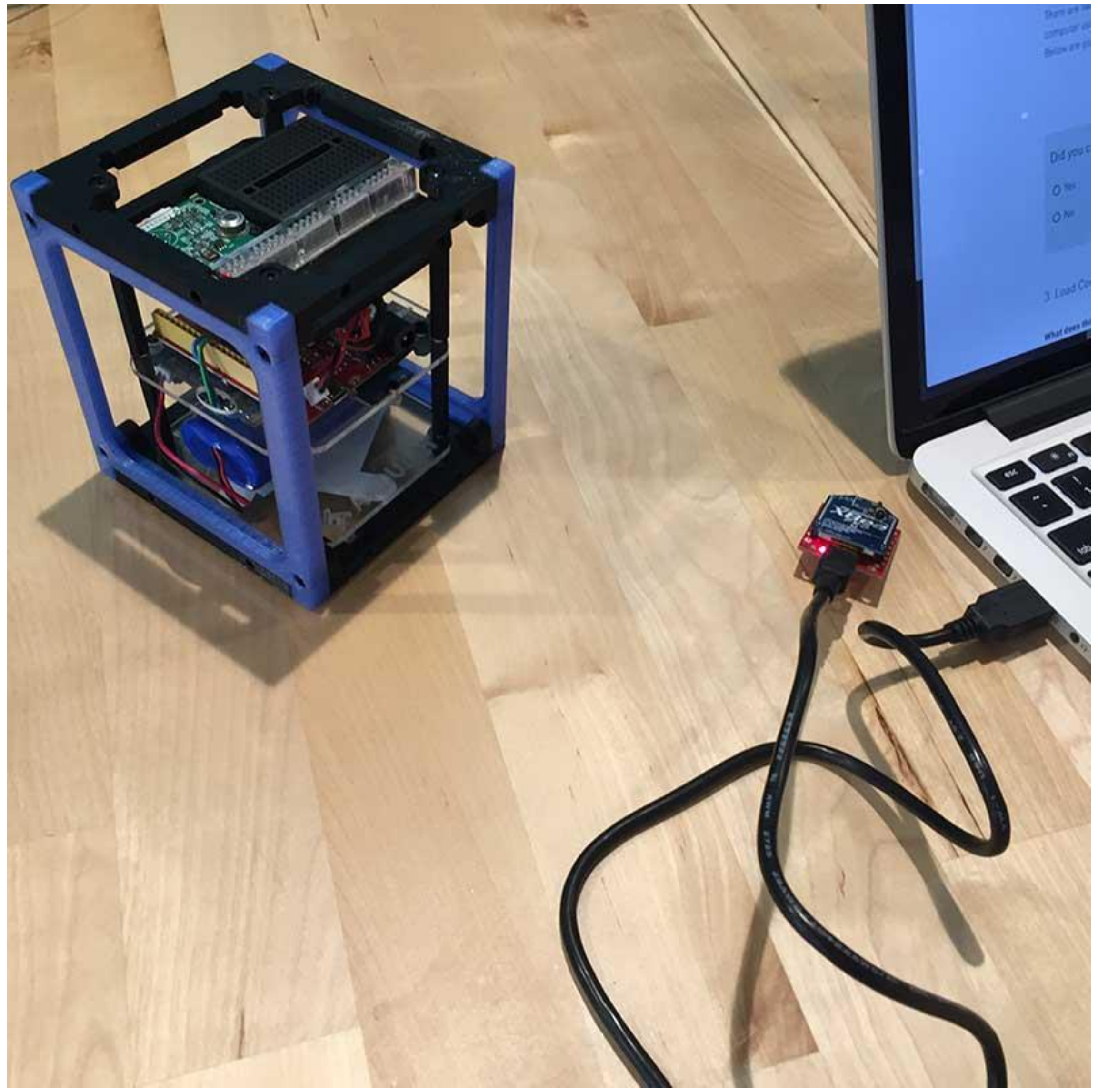


Figure: Illustration of one network

Xbee on Ardusat A(Target) → A network → Xbee on A Shield

Xbee on Ardusat B(Chaser) → B network → Xbee on B Shield

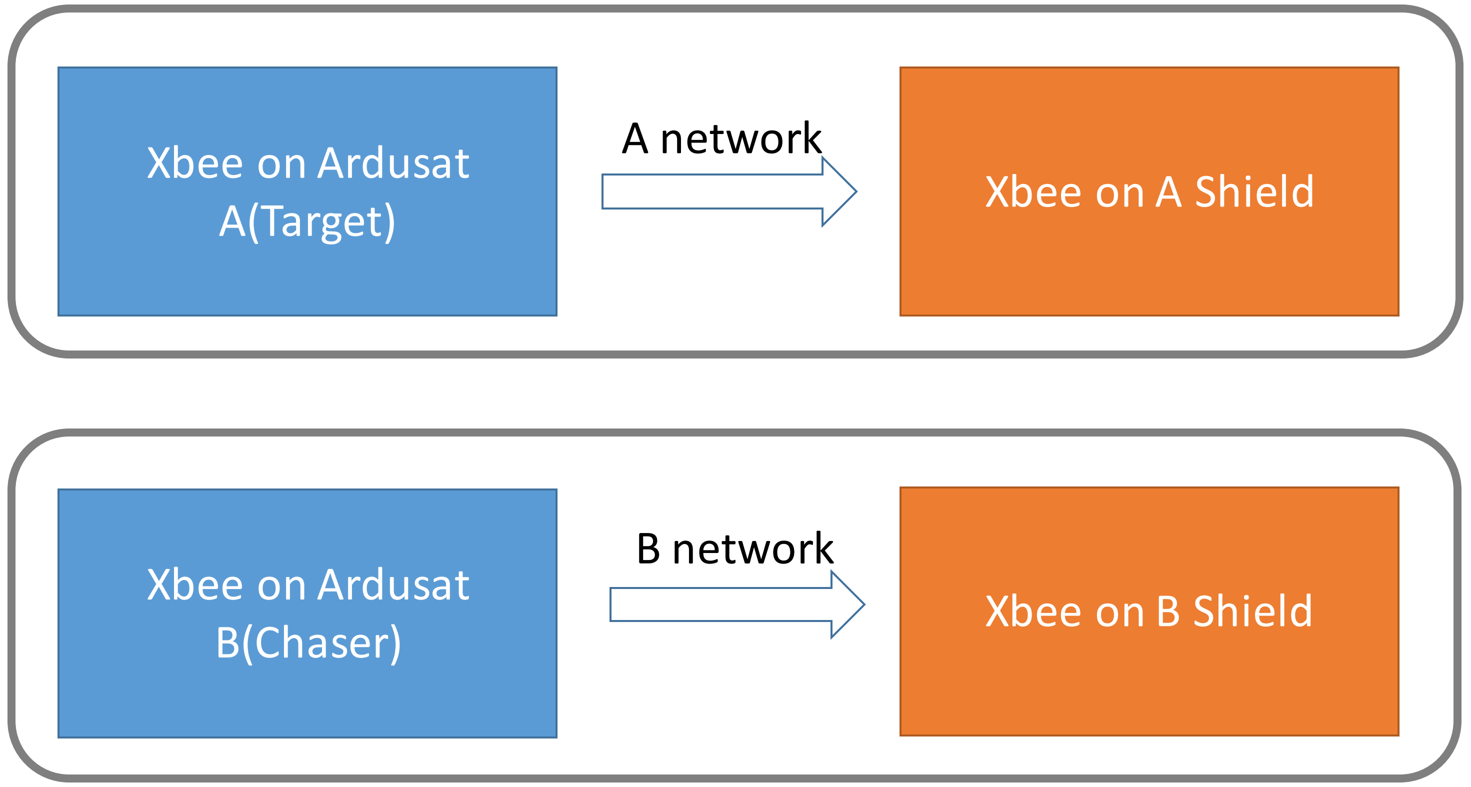
The two network should be separated. The wireless network transmission should not be interfered by the other network.

Wireless communication Setup

Archived lowest interference setting

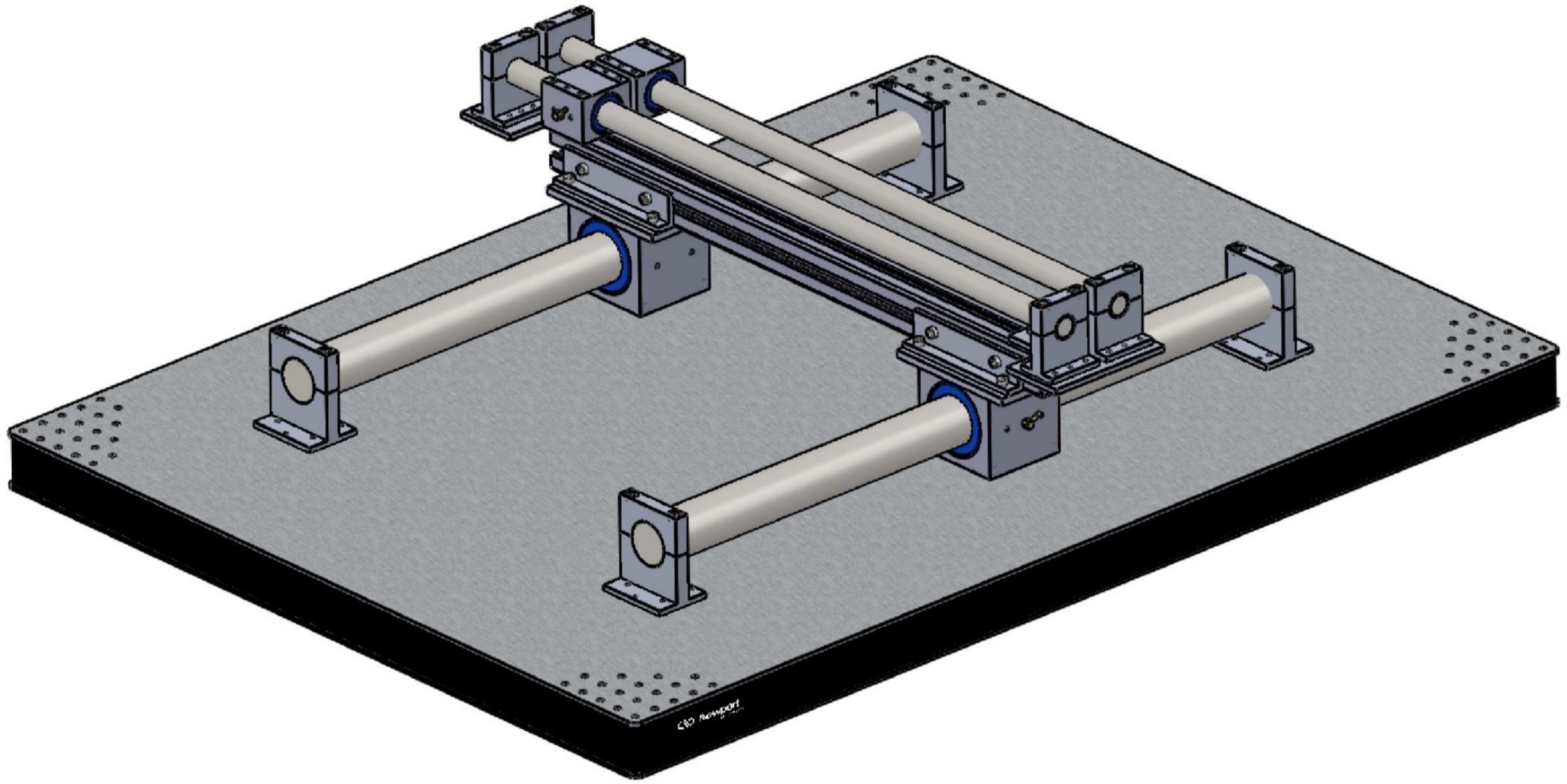
Setting \ Xbee part	A shield	On Ardusat A	B shield	On ArduSat B
Channel	C		17	
Personal area network ID	3332		83D5	
Destination Address High	0	0	0	13A200
Destination Address Low	35	0	1234	4163E25D
16-bit Source Address	0	35	4321	1532
Serial Number High	13A200			
Serial Number Low	4167BD1E	4163E2BA	4163E25D	4167BD2E
Interface Data Rate	57600			

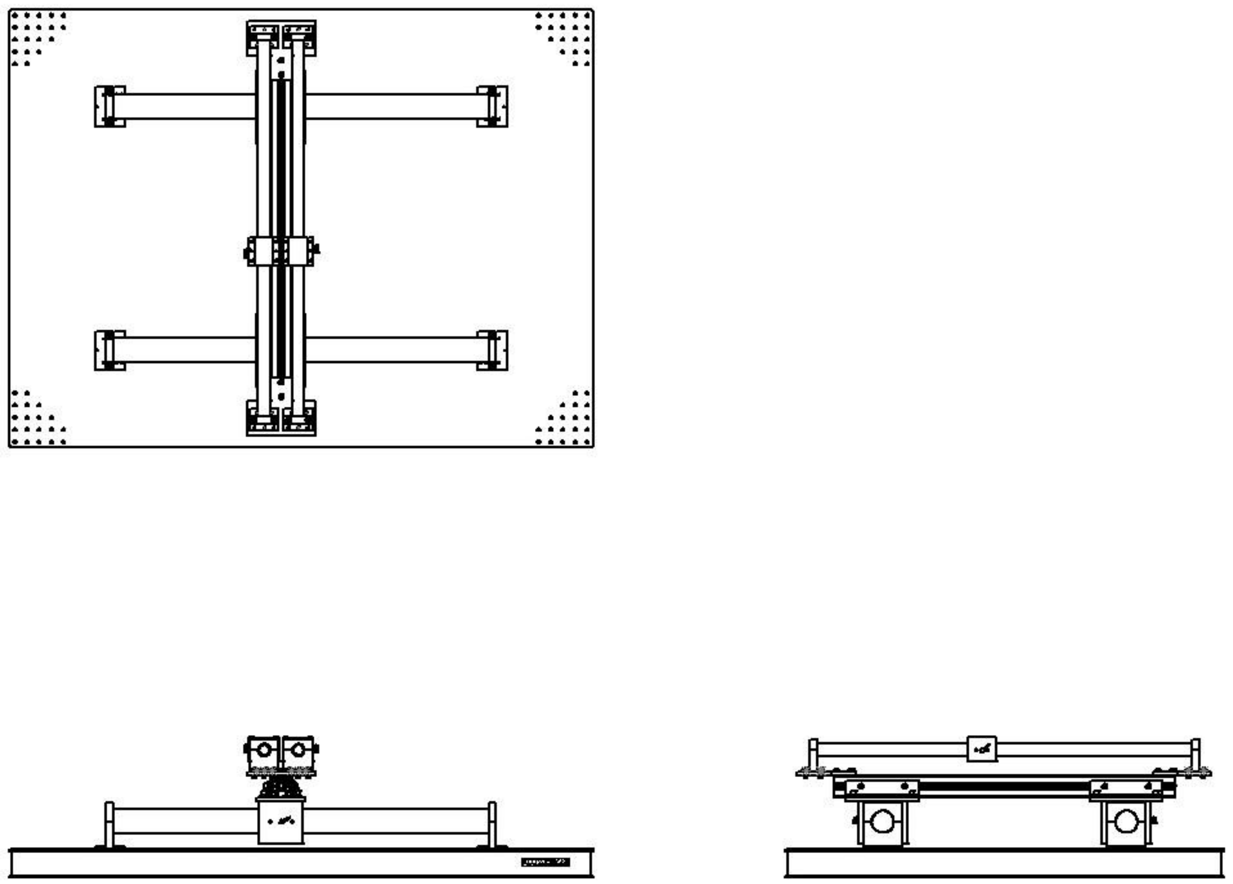
Table: Xbee Part setting



Key point: Each following one way and against the other at the same time respectively

Testbed fabricating





Acknowledgement

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The most valuable things I learned are the self-learning skill, problem-solving logical thinking and markdown custom. I am really thankful to them.

Secondly I would also like to thank my friends and PhD colleagues who helped me a lot in finalizing this project within the limited time frame.

Thank you for listening