INDIAN CONTROL CONFERENCE
20-22 Dec 2021 • IIT-Bombay

CONTROL SYSTEM DESIGN FOR MIMO SYSTEM USING BOND GRAPH REPRESENTATION

- QUADCOPTER AS A CASE STUDY

IRENE GRACE KAROT POLSON
Senior Undergraduate
Dept of Aerospace Engineering
Indian Institute of Technology Kanpur
Kanpur, India

R.S. MOHANKUMAR
Assistant professor
Dept of Mechanical Engineering
Coimbatore Institute of Technology,
Coimbatore, India

N. SELVAGANESAN
Professor
Dept of Avionics, Indian Institute of
Space Science and Technology
Thiruvananthapuram, India

OBJECTIVE

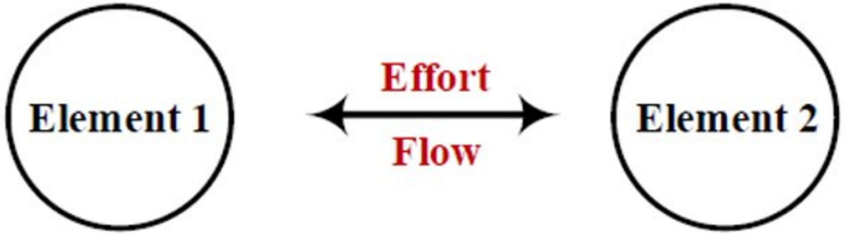
The paper approaches the design and simulation of physical systems using bond graph representations.

- It was developed by Prof. Henry M. Paynter, an MIT professor focused on systems engineering.
- Bond graph is a methodology that allows the graphical representation of multidisciplinary physical systems.
- Engineering systems need to be modelled so that the relationship between design variables and the corresponding designed system's response can be studied, understood and improved in a better way when compared to the conventional approaches of system representations .

We have chosen the well-known quadcopter system as a case study of a MIMO system modelled using Bond Graph representation.

INTRODUCING - BOND GRAPH

- In bond graph theory, every element is represented by a multiport.
- Ports are connected by bonds corresponding to flow of energy between elements.



Power = Effort x Flow

Basic Blocks of Bond Graph Representation:

1-port elements

- C-type
- I-type
- R-type
- Effort sources
- Flow sources

2-port elements

- Transformers
- Gyrators

Multi-port elements

- 0-junctions
- 1-junction

INTRODUCING - BOND GRAPH

Advantages of bond graph modelling:

Multi-domain system

Bond graphs are domain neutral. The same elements are used for every physical domain. Allows coupled modelling of mechanical and electrical elements which is useful control system design of mechanical models coupled with electrical signals.

Elemental Information

The graphical representation makes use of flow and energy of elements, and each elements information can be accessed. This allows for comprehensive analysis of the system at hand according to requirement.

Auto State-Space Formulation

Automatic state-space equations - Bond graph models created in 20 SIM can generate state-space equations of the system modelled from the graphical representations. This is an easier method to obtained state space approaches equations for systems with large number of states.

- We have access to very intricate details of the system though this representation.
- This helps improve maintenance cycles allowing to meet different objectives such as reliability cost and performance.
- Models made using bond graphs can easily be modified.

LITERATURE SURVEY

For our specific quadcopter modelling problem there are a few papers that have studied various aspects of it.

[1]-3] Use of bond graph for attitude and altitude control has been studied using linearised Newton-euler formulations: In these studies, only the system model is modelled using bond graph represenation.

[4] A separate study has explored modelling integral and derivative components for control system formulation using bond graph representation

PROBLEM STATEMENT

The quadcopter model along with PID controller is represented using bond graph approach.

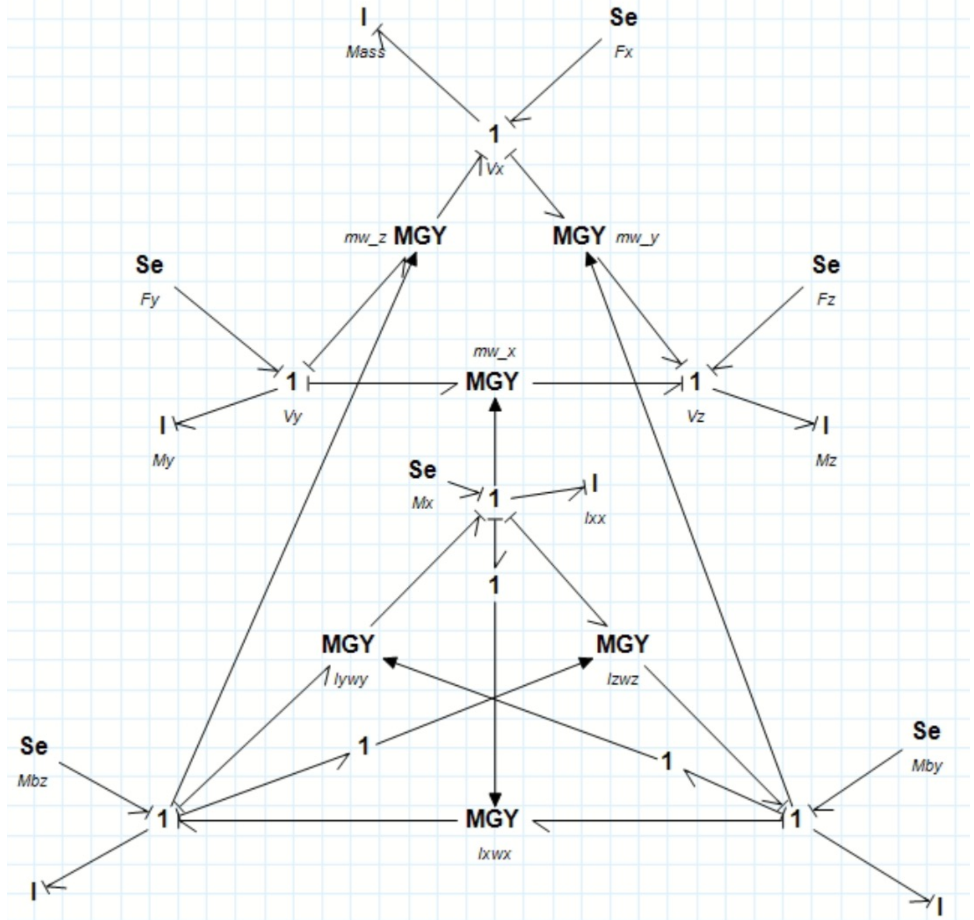
- Reduced bond graph model is derived, and feedback is obtained from inertial elements of the reduced model.
- The entire simulation is carried out using 20-sim software under position tracking and disturbance rejection conditions.
- The PID controller is obtained to achieve stability in both the attitude and position of quadcopter.

QUADCOPTER DESCRIPTION

The equations represented using bond graph:

$$F_{x,external} = m\ddot{x} + m(\dot{z}\omega_y - \dot{y}\omega_z)$$
$$F_{y,external} = m\ddot{y} + m(\dot{x}\omega_z - \dot{z}\omega_x)$$
$$F_{z,external} = m\ddot{z} + m(\dot{y}\omega_x - \dot{x}\omega_y)$$
$$M_{x,external} = I_x\dot{\omega}_x - (I_y - I_z)\omega_y\omega_z$$
$$M_{y,external} = I_y\dot{\omega}_y - (I_z - I_x)\omega_z\omega_x$$
$$M_{z,external} = I_z\dot{\omega}_z - (I_x - I_y)\omega_x\omega_y$$

Bond graph representation of Quadcopter:

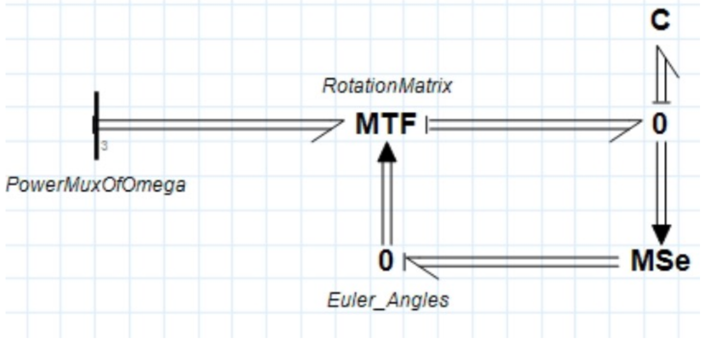


REFERENCE FRAME TRANSFORMATION

Rotation Matrix:

$$R_b^I = \begin{bmatrix} 1 & 0 & -sin(\theta) \\ 0 & cos(\phi) & sin(\phi)cos(\theta) \\ 0 & -sin(\phi) & cos(\phi)cos(\theta) \end{bmatrix}$$

Transformation and integration:



- The angular rates and velocities obtained from the quadcopter model are in the body frame.
- The rotation matrix as well as controller needs angles and distance in the inertial frame.

Rotation and integration of angular rates and velocities are carried out simultaneously.

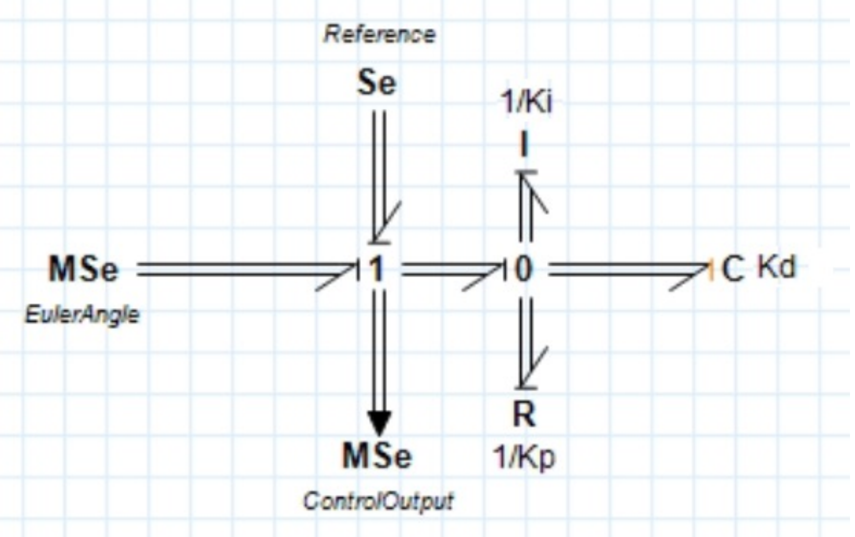
CONTROL SYSTEM DESIGN

Effort Source --> Reference angle and position

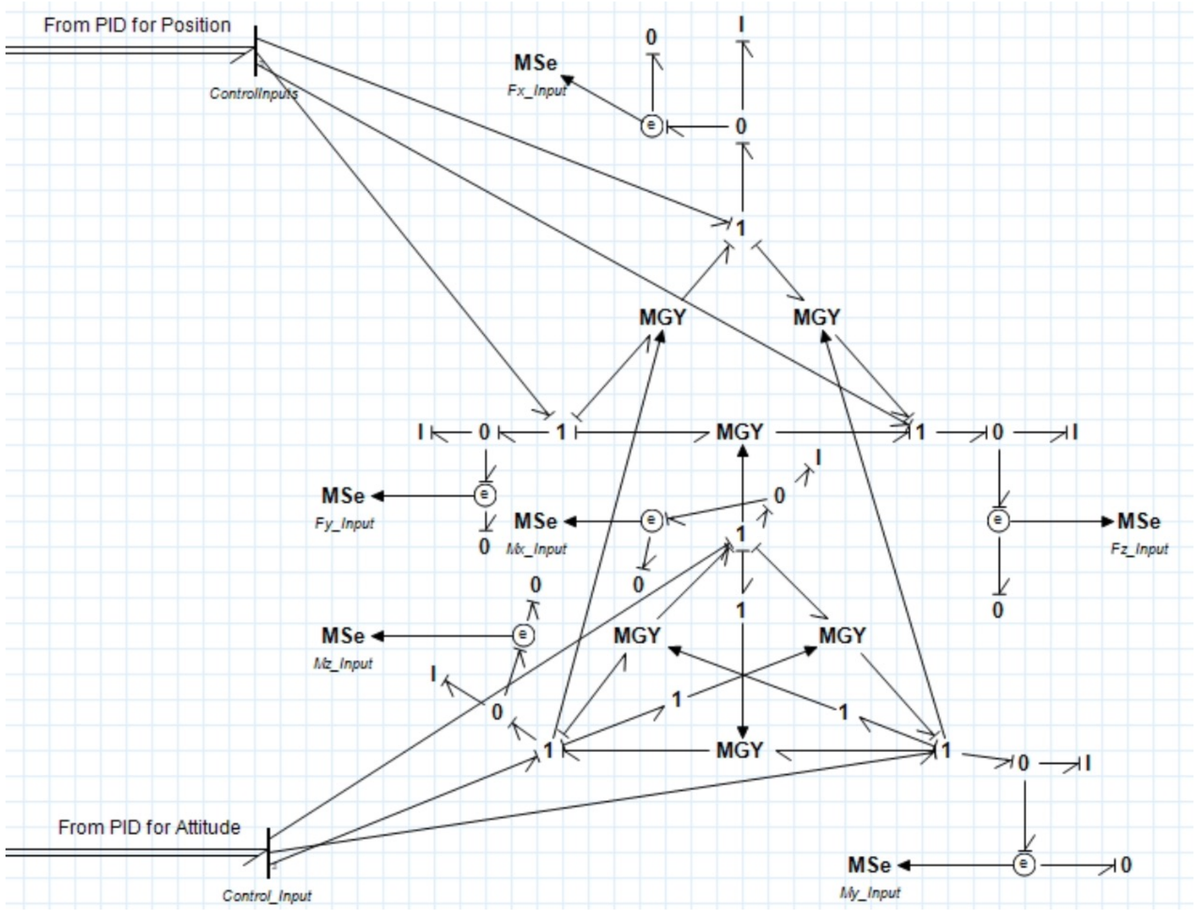
Resistance R --> 1 / kp

Capacitance C --> kd

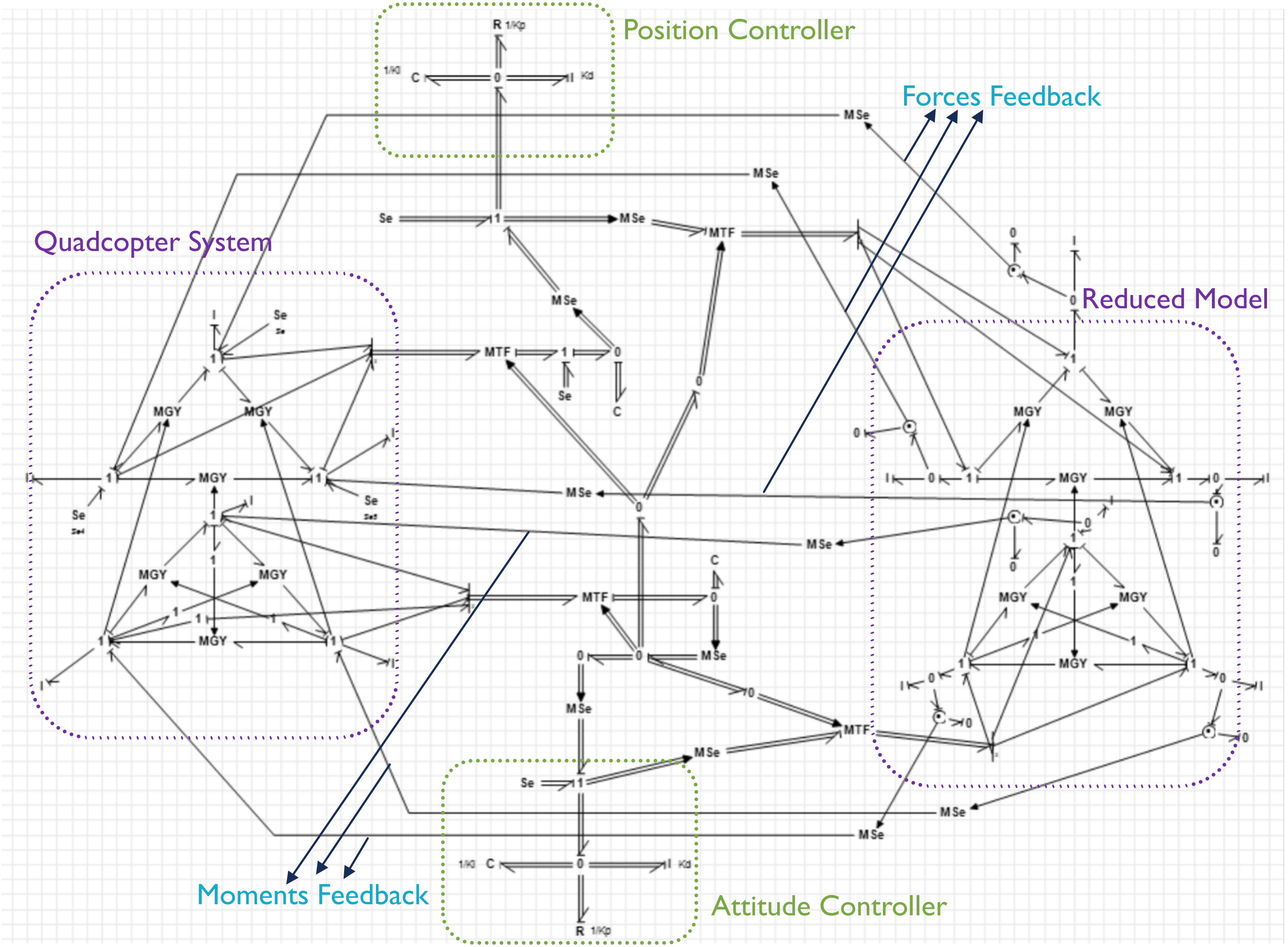
Inductance I --> 1 / ki



The control output is fed to a reduced model of the quadcopter the determines the forces needed for control.



COMPLETE SYSTEM MODELLED USING BOND GRAPH



SIMULATION

Quadcopter and control parameters :

Parameters	Value
Mass of quadcopter m	1 kg
Moment of inertia I_x	0.1 kg m^2
Moment of inertia I_y	0.1 kg m^2
Moment of inertia I_z	0.1 kg m^2
Position control K_p, K_i, K_d	10, 1, 1
Attitude control K_p, K_i, K_d	1, 0.1, 1

- The control parameters are obtained by trial and error till satisfactory results were obtained.

References and Disturbances:

- Case 1: Stabilizing
  Zero Position reference + disturbance
- Case 2: Tracking
  Non-zero position reference + disturbance

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 10 \\ 10 \\ 10 \end{bmatrix}$$

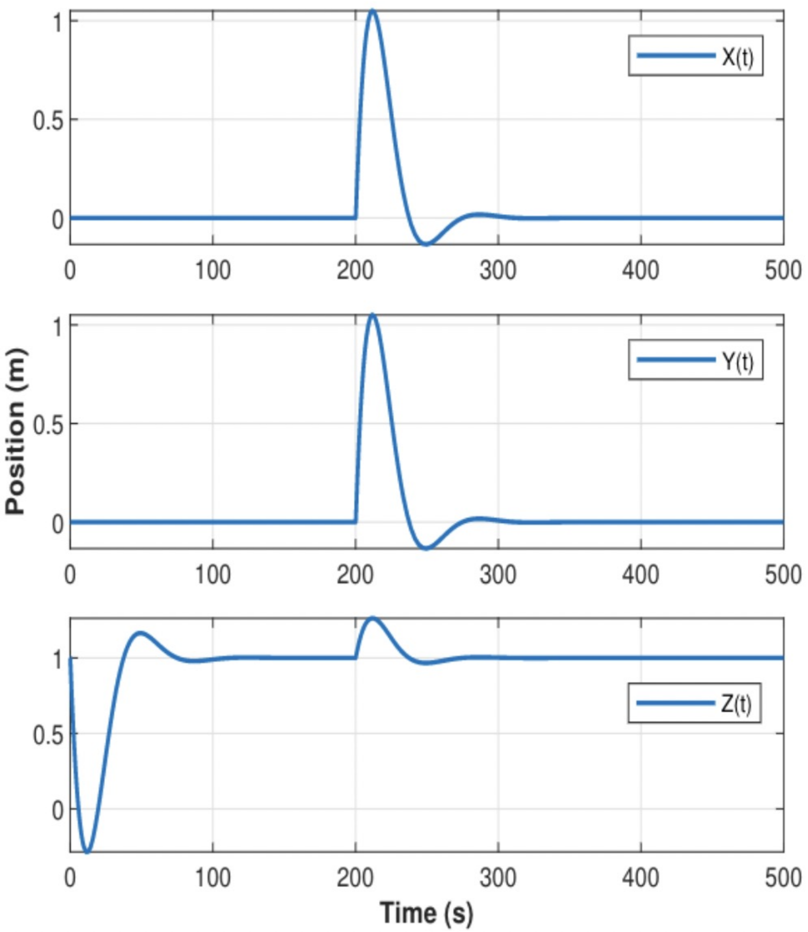
- The angle references are set to zero.

- A disturbance of 2N is applied at 200s which needs to be stabilized by the quadcopter.

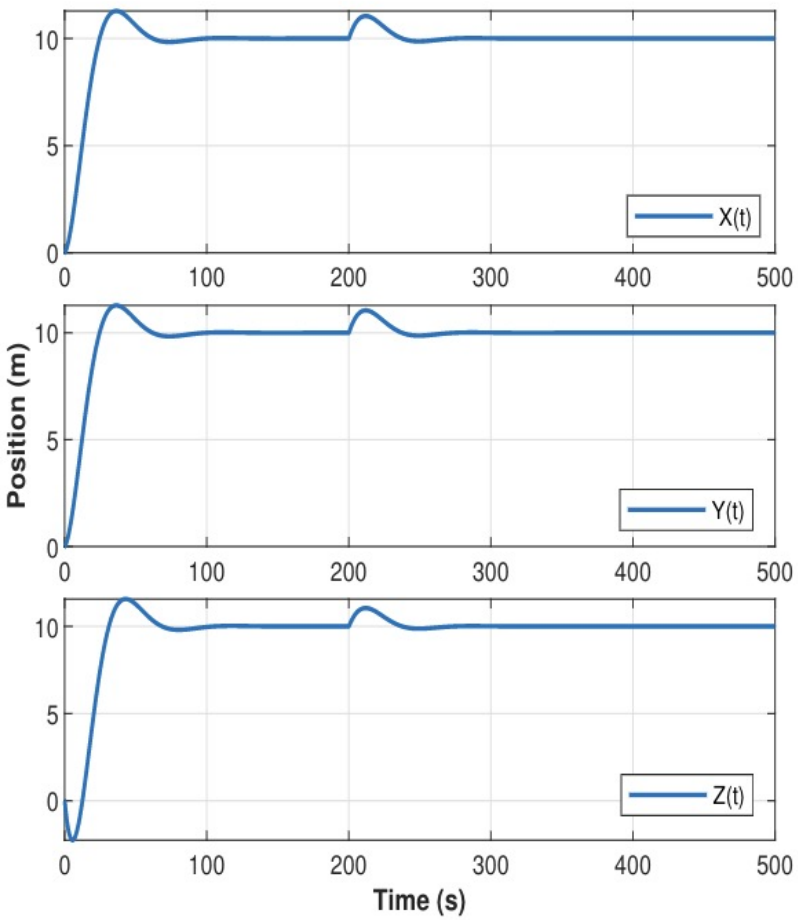
RESULTS

- The quadcopter initially tries to stabilize itself in the Z-direction as response to gravity force.
- The responses for the disturbance are similar in the X and Y direction due to symmetric in moment of inertia.
- The quadcopter can return to its command position after the disturbance in case 1
- The Quadcopter can reach the reference position in case 2

Case 1: Stabilizing



Case 2: Tracking

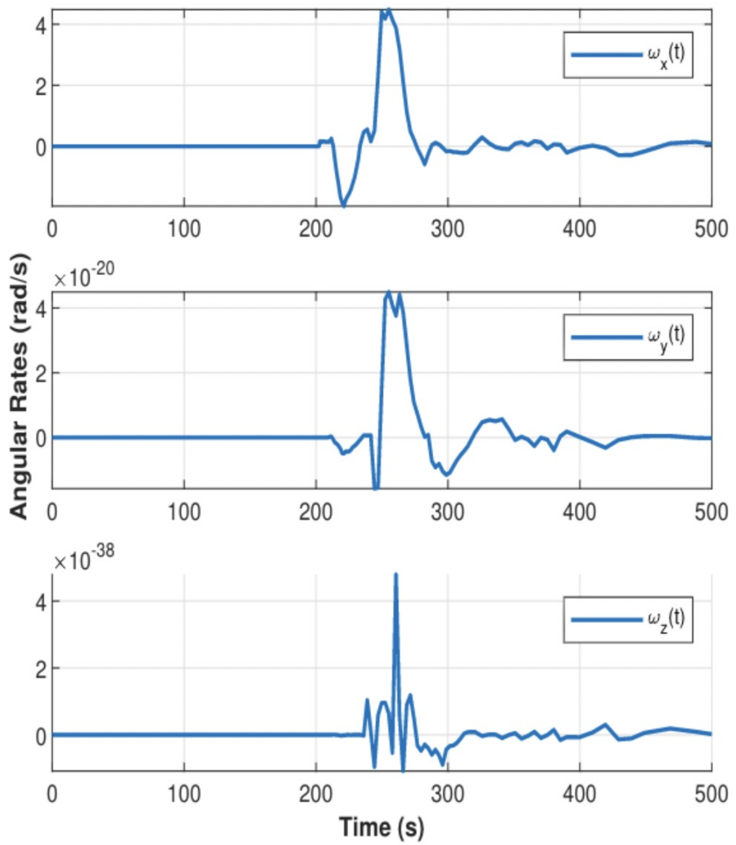


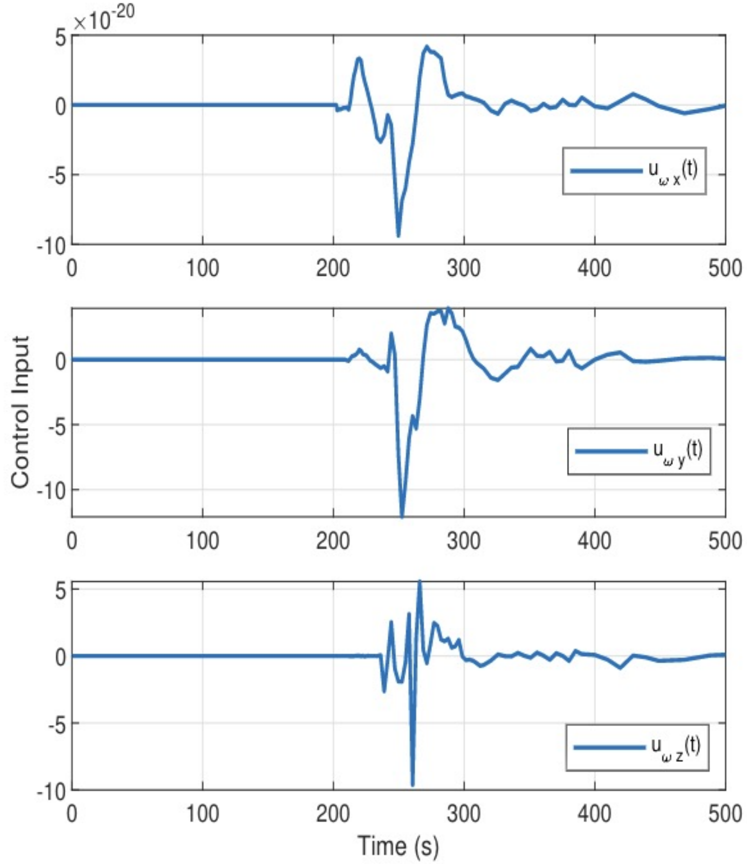
RESULTS

Reponses and Control outputs obtained the attitude controller that led to the response.

Case 1: Stabilizing

The angles adjust itself to facilitate translation of position back to its reference and further stabilizes itself.





CONCLUSION

- The entire model as well as the PID control had been represented using bond graphs and hence intricate details of each element of the system can be obtained and used for further improvements of the system and its life-cycle.
- The reduced bond graph model served the purpose of obtaining the dynamic inversion of the non-linear system.
- PID controllers were used for both position tracking and attitude stabilization.
- Simulations were conducted to show the position tracking, angle stabilizing capabilities of the system as well as the robustness towards disturbances.

Future scope:

- Advanced controllers can be used in place of the modelled PID controller to obtain different stability characteristics.
- The controller gains in this paper have been manually tuned using the simulation of the bond graph model. This process can be improved, and optimal controller gains can be obtained by innovative use of bond graph modelling methods.

REFERENCE

1. Habibi,M., Ghane, M., Novinzadeh, A. B, "Modeling integrative and derivative systems in bond graph modeling and using it in adaptive control," Life Science Journal, July 2013, Vol 10, pp 58-69.
2. Matouk, D., Ahmad, F., Kumar, P., Merzouki, R., Singh, M., & Abdessemed, F., "Bond Graph Model-Based Control of the Quadcopter Dynamics," 7th International Conference on Systems and Control (ICSC), pp 435-440, 2018.
3. Hossain, M. R., & Krouglicof, D. N., "Multi-body Dynamics Modeling & Control of Quadrotor Helicopter using Bond Graph," International Conference on Bond Graph Modeling and Simulation, July 2016.
4. Hossain, M. R., Rideout, D. G., & Krouglicof, D. N., "Bond graph dynamic modeling and stabilization of a quad-rotor helicopter," Spring Simulation Multiconference on - SpringSim '10, April 11-15, 2010.
5. Gheorghita, D., Vintu, I., Mirea, L., and Braescu, C., "Quadcopter control system," 19th International Conference on System Theory, Control and Computing (ICSTCC), 2015.
6. Islam, M., Okasha, M., & Idres, M. M., "Dynamics and control of quadcopter using linear model predictive control approach," IOP Conference Series Materials Science and Engineering , December 2017.
7. Borutzky, W., "Bond graph modelling and simulation of multidisciplinary systems – An introduction," Simulation Modelling Practice and Theory, Vol 17, No.1, pp 3-21, January 2009.
8. Srinivasarao, G., Samantaray, A. K., Ghoshal, S. K., "Bond graph modeling and multi-body dynamics of a twin rotor system," Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, pp 1-28, February 12, 2020.
9. Ahmad, F., Kumar, P., Bhandari, A., & Patil, P. P. , "Simulation of the Quadcopter Dynamics with LQR based Control," Materials Today, Vol. 24, No.23, January 2020, pp 326-332.
10. Naidoo, Y., Stopforth, R., Bright, G., "Quad-Rotor Unmanned Aerial Vehicle Helicopter Modelling \& Control," International Journal of Advanced Robotic Systems, Vol. 8, No.4, pp 139-149, January 1, 2011.

Thank you!