Robust Control of Quadrotors

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Outline

Outline

Unmanned Aerial Vehicles in General

Unmanned aerial vehicles are flying machines with no human beings onboard.

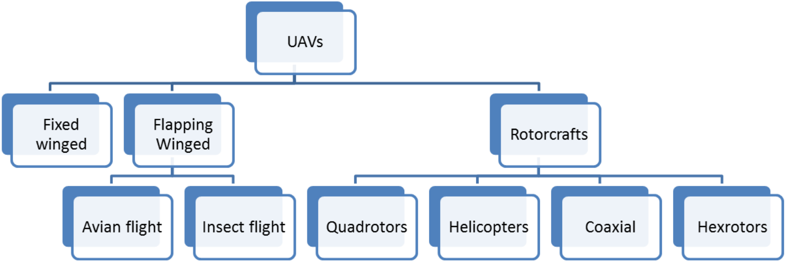

Figure 1: Different Types of UAVs

Quadrotors $\subset$ Rotorcrafts $\subset$UAVs

Quadrotor

- An UAV with four rotors.
- 6 DOF - 4 inputs $= 2 \neq 0 \Rightarrow$ underactuated
- Adjacent rotors have opposite sense of rotation to balance the total angular momentum.
- Can perform VTOL, hover and slow precise movements

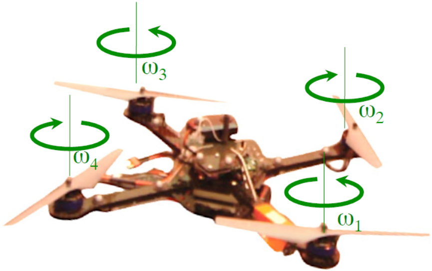

Figure 2: Quadrotor UAV

Components of Autonomous Flight

- **State Estimation:** Estimate the linear and angular positions and velocities.
  - Motion Capture System
  - Global Positioning System(GPS)
  - Simulataneous Localization and Mapping(SLAM)
- **Control:** Command actuators to produce desired motion
- **Mapping:** Vehicle must be able to know its surroundings
- **Planning:** The vehicle must be able to compute a trajectory given a set of obstacle and a destination

Applications

- Precision Farming
- Photography
- Rescue
- Manipulation
- Swarm Robotics
- Military

Challenges

- Underactuated system
- Weight of components
- Lack of a reliable power source
- Legal aspects of use

Outline

Mechanics

- The forces acting on the system are the thrusts F_i from each of the rotor and the force of gravity $-mg\mathbf{a}_3$.
- The moments acting on the system are the moments due to each of the thrust and the drag moment M_i which is generated due to the propellor rotation.

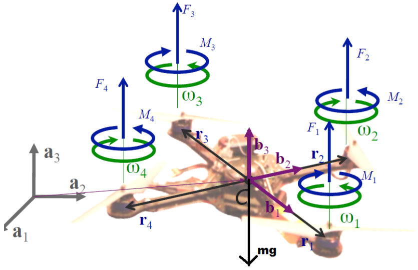

Figure 3: Free Body Diagram of a Quadrotor UAV

Mechanics

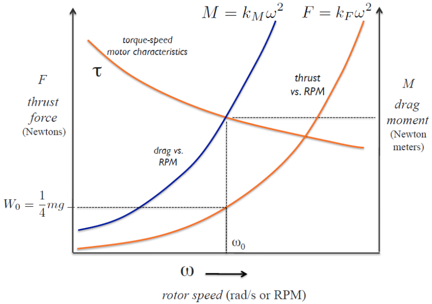

Figure 4: Thrust F_i, Drag Moment M_i and Motor Torque Speed Chacteristics τ vs ω

Mechanics

- Motor Speeds at Hover Configuration:

$$k_F\omega_0^2 = \frac{mg}{4} \tag{1}$$

- Motor Torques and Drag Torque (They have same magnitude but opposite signs):

$$M_i = \tau_i = k_M\omega_i^2 \tag{2}$$

- Thrust

$$F_i = k_F\omega_i^2 \tag{3}$$

Mechanics

- Resultant Force:

$$F = F_1 + F_2 + F_3 + F_4 - mg\mathbf{a}_3 \tag{4}$$

- Resultant Moment:

$$M = r_1 \times F_1 + r_2 \times F_2 + r_3 \times F_3 + r_4 \times F_4 + M_1 + M_2 + M_3 + M_4 \tag{5}$$

In Equilibrium, the resulant force and torque are zero. If it is non zero then the robot accelerates. A combination of motor thrusts and the weight determines the net linear and angular acceleration of the robot.

Quadrotor Dynamics

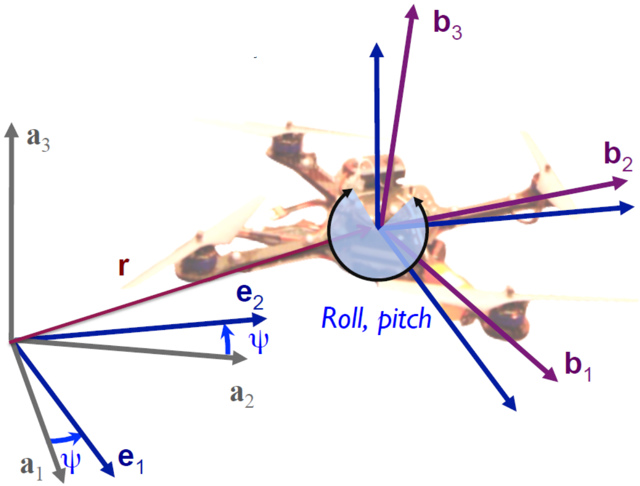

Figure 5: Different Frames

Quadrotor Dynamics

- Rotation Matrix: Following the ZXY Euler Angles

$$
{}^{W}R_{B} = \begin{bmatrix} c\psi c\theta - s\phi s\psi s\theta & -c\phi s\psi & c\psi s\theta + c\theta s\phi s\psi \\ c\theta s\psi + s\phi c\psi s\theta & c\phi c\psi & s\psi s\theta - c\theta s\phi c\psi \\ -c\phi s\theta & s\phi & c\phi c\theta \end{bmatrix} \tag{6}
$$

$\phi =$ Roll, $\theta =$ Pitch and $\psi =$Yaw

Quadrotor Dynamics

- Linear Motion Equation in World Frame $\mathbf{a}_1\mathbf{a}_2\mathbf{a}_3$

$$m\ddot{r} = \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix} + {}^W R_B \begin{bmatrix} 0 \\ 0 \\ F_1 + F_2 + F_3 + F_4 \end{bmatrix} \tag{7}$$

- Angular Motion Equation in the Body Frame $\mathbf{b}_1\mathbf{b}_2\mathbf{b}_3$

$$\mathbf{I} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} L(F_2 - F_4) \\ L(F_3 - F_1) \\ M_2 + M_4 - M_1 - M_3 \end{bmatrix} - \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \mathbf{I} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{8}$$

where, $\mathbf{r} = [x \;\; y \;\; z]^T$, $I =$ Moment of Interia, $m =$ Mass of the System, $[p \;\; q \;\; r]$: Body Angular Velocities

Quadrotor Dynamics

- The relation ship between body angular velocities and the rate of change of Roll, Pitch and Yaw.

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} c\theta & 0 & -c\phi s\theta \\ 0 & 1 & s\phi \\ s\theta & 0 & c\phi c\theta \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \tag{9}$$

Quadrotor Dynamics

- Thrust Input: $u_1 = F_1 + F_2 + F_3 + F_4$
- Torque Input: $u_2 = \begin{bmatrix} L(F_2 - F_4) \\ L(F_3 - F_1) \\ M_2 + M_4 - M_1 - M_3 \end{bmatrix}$

This work has been done in the space of u_1 and u_2 without going into details of the actuators (F_i and M_i).

Outline

Basic Idea

- Design controllers that allow the quadrotor to follow a prescribed trajectory.
- Many Linear and Non Linear Methodologies developed.
    1. PD Control
    2. PID Control
    3. LQ Control
    4. Sliding Mode Control
    5. Backstepping Control
    6. Integrator Backstepping Control

Controllers Implemented

1. PD Control
2. Sliding Mode Control
3. Backstepping Control

Basic Block Diagram

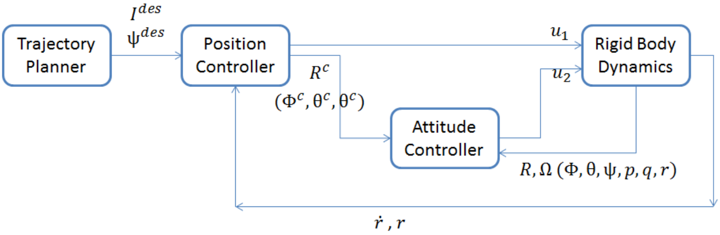

Figure 6: Control Block Diagram

Outline

PD Control

This control law works well under hover conditions. Linearizing the dynamic model at the hover configuration, where we have: $u_1 \approx mg$, $\theta \approx 0$, $\phi \approx 0$, $\psi \approx \psi_0$, $u_2 \approx 0$, $u_2 \approx 0$, $p \approx 0$, $q \approx 0$ and $r \approx 0$. Under these approximations, the system model is reduced to:

$$m \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} (c\psi s\theta + c\theta s\phi s\psi)u_1 \\ (s\psi s\theta - c\theta s\phi c\psi)u_1 \\ -mg + c\phi c\theta u_1 \end{bmatrix} \tag{10}$$

$$I \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = u_2 \tag{11}$$

PD Control

The reference trajectory is: $r_{ref} = \begin{bmatrix} x_{des} & y_{des} & z_{des} & \psi_{des} \end{bmatrix}^T$ The commanded linear accelerations can be calculated as:

$$\begin{aligned} \ddot{x}_c &= \ddot{x}_{des} + k_{dx}(\dot{x}_{des} - \dot{x}) + k_{px}(x_{des} - x) \\ \ddot{y}_c &= \ddot{y}_{des} + k_{dy}(\dot{y}_{des} - \dot{y}) + k_{py}(y_{des} - y) \\ \ddot{z}_c &= \ddot{z}_{des} + k_{dz}(\dot{z}_{des} - \dot{z}) + k_{pz}(z_{des} - z) \end{aligned} \tag{12}$$

The commanded roll, pitch and yaw are:

$$\begin{aligned} \phi_c &= \frac{1}{g}(\ddot{x}_c sin(\psi_{des}) - \ddot{y}_c cos(\psi_{des})) \\ \theta_c &= \frac{1}{g}(\ddot{x}_c cos(\psi_{des}) + \ddot{y}_c sin(\psi_{des})) \\ \psi_c &= \psi_{des} \end{aligned} \tag{13}$$

PD Controller Output

Using Equations 12 and 13

$$
\begin{aligned}
u_1 &= m(g + \ddot{z}_c) \\
u_2 &= \mathbf{I} \begin{bmatrix} k_{p\phi}(\phi_c - \phi) + k_{d\phi}(p_c - p) \\ k_{p\theta}(\theta_c - \theta) + k_{d\theta}(q_c - q) \\ k_{p\psi}(\psi_c - \psi) + k_{d\theta}(r_c - r) \end{bmatrix}
\end{aligned} \tag{14}
$$

Using Equation 9 one can get $[p_c, q_c, r_c]^T$.

PD Control Results: Sans disturbance

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PD Control Results: Sans disturbance

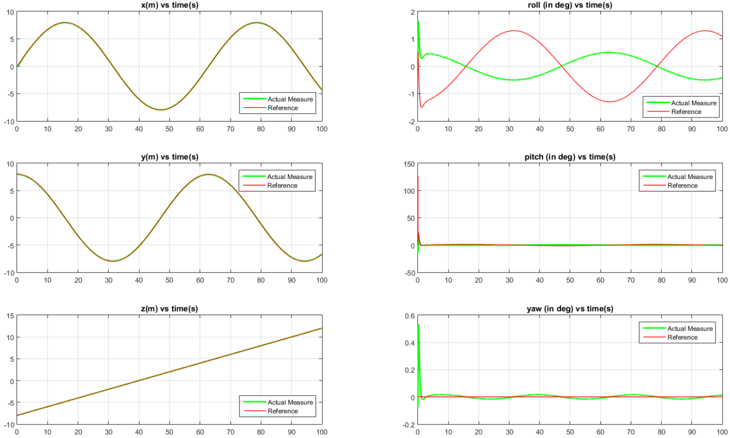

Figure 7: Position and Orientation vs Time

PD Control Results: Sans disturbance

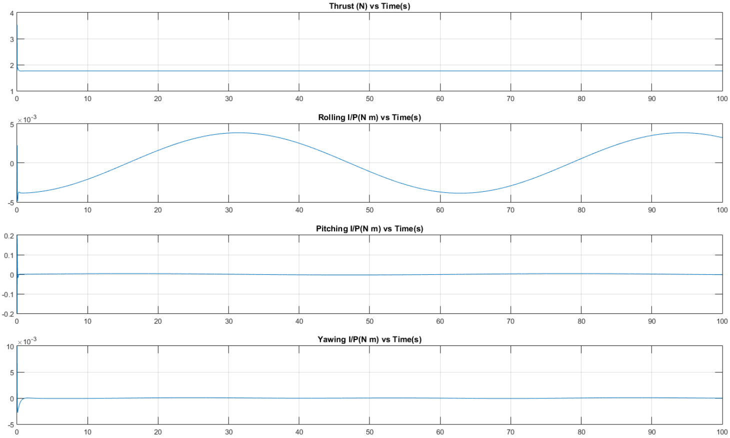

Figure 8: Thrust, Rolling, Pitching and Yawing Inputs vs Time

PD Control Results: Sans disturbance

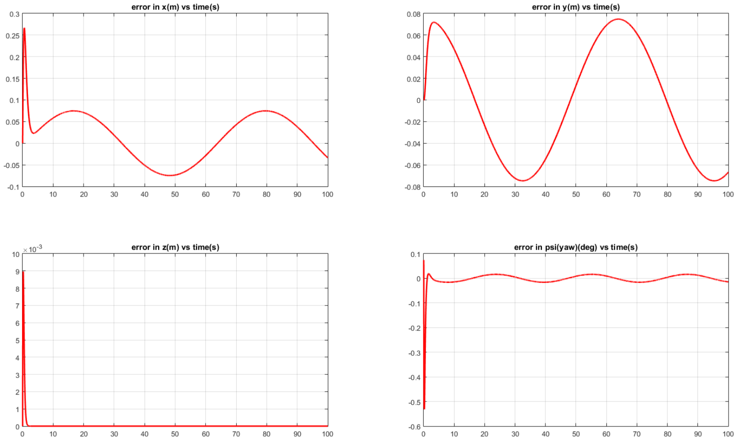

Figure 9: Errors in x,y,z and yaw

PD Control Results: With disturbance

PD Control Results: With disturbance

PD Control Results: With disturbance

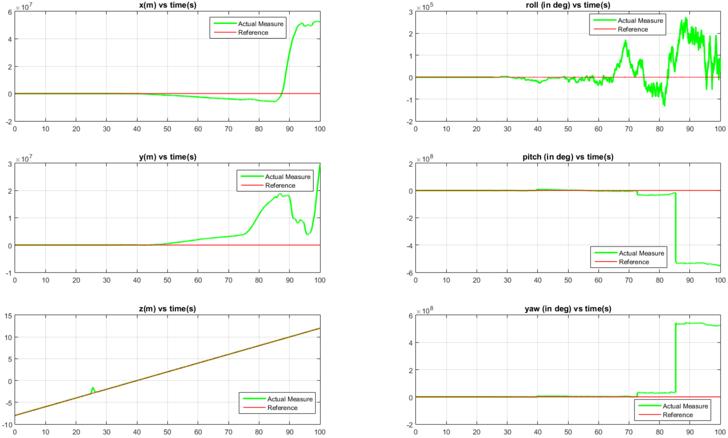

Figure 10: Position and Orientation vs Time [With Disturbance at 25s]

PD Control Results: With disturbance

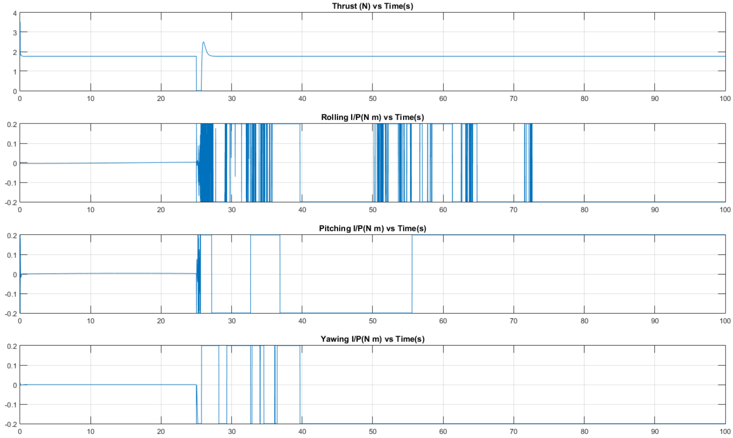

Figure 11: Thrust, Rolling, Pitching and Yawing Inputs vs Time [With Disturbance at 25s]

PD Control Results: With disturbance

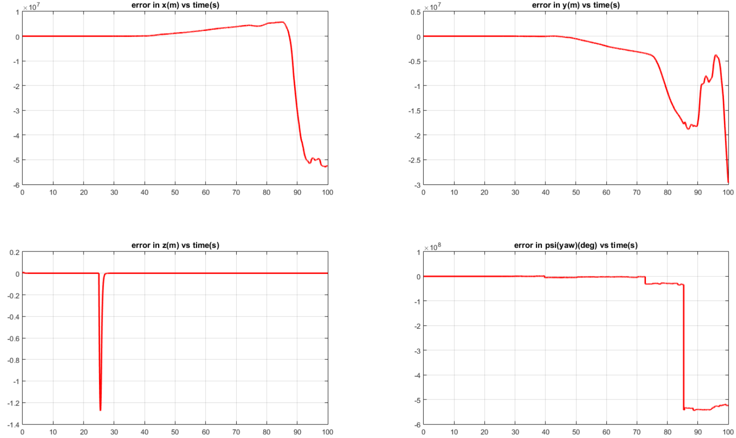

Figure 12: Errors in x,y,z and yaw [With Disturbance at 25s]

PD Control: Conclusion

The advantages of Proportional Derivative (PD) Control are::

a. Easy to understand and implement.
b. Less tuning parameters.
c. Tuning process is not complicated

The disadvantages of PD Control are:

a. The derivative term creates problem in real systems. It amplifies the noise.
b. The control is not robust to disturbances and parameter variations.

Outline

SMC

- Non Linear Robust Control Technique.
- Variable Structure Control(VSC).
- Controller output is discontinous, high frequency switching controller.

SMC

- The Sliding Mode Controller is designed only for the attitude control part.
- PD control is used for altitude control owing to simplicity of the altitude control equation.

SMC

Approximating with near hover conditions: $p \approx \dot{\phi}$, $q \approx \dot{\theta}$ and $r \approx \dot{\psi}$.
The dynamics of attitude is given as:

$$\mathbf{I}\ddot{\omega} = u_2 - \dot{\omega} \times \mathbf{I}\dot{\omega} \Rightarrow \ddot{\omega} = -\mathbf{I}^{-1}\dot{\omega} \times \mathbf{I}\dot{\omega} + \mathbf{I}^{-1}u_2 \tag{15}$$

Where, $\omega = \begin{bmatrix} \phi & \theta & \psi \end{bmatrix}^T$
The error $e(t)$ is defined as, $e(t) = \omega - \omega_c$. Since the relative degree of the system is 2, the sliding variable can be defined as:

$$s = \dot{e} + \lambda e$$

SMC

Differentiating once,

$$\begin{aligned}
\dot{s} &= \ddot{e} + \lambda \dot{e} \\
\dot{s} &= \ddot{\omega} - \ddot{\omega}_c + \lambda(\dot{\omega} - \dot{\omega}_c) \\
\dot{s} &= -\mathbf{I}^{-1}\dot{\omega} \times \mathbf{I}\dot{\omega} + \mathbf{I}^{-1}u_2 - \ddot{\omega}_c + \lambda(\dot{\omega} - \dot{\omega}_c) \\
\dot{s} &= -\mathbf{I}^{-1}\dot{\omega} \times \mathbf{I}\dot{\omega} - \ddot{\omega}_c + \lambda(\dot{\omega} - \dot{\omega}_c) + \mathbf{I}^{-1}u_2 \\
\dot{s} &= \alpha_{SM} + \beta_{SM}u_2
\end{aligned} \tag{16}$$

Where $\alpha_{SM} = -\mathbf{I}^{-1}\dot{\omega} \times \mathbf{I}\dot{\omega} - \ddot{\omega}_c + \lambda(\dot{\omega} - \dot{\omega}_c)$ and $\beta_{SM} = \mathbf{I}^{-1}$.
ω_c can be calculated from Equation 12 and 13.

SMC

For nominal control, the control law will be chosen as:

$$u_2 = \beta_{SM}^{-1}(-\alpha_{SM} + v)$$

For sliding mode, v has to be chosen as:

$$v = -K * sign(s)$$

Here, K is the sliding mode gain matrix. Using the above equations, the control input for controlling the altitude is:

$$u_2 = \beta_{SM}^{-1}(-\alpha_{SM} - K * sign(s)) \tag{17}$$

SMC

λ and K are gain matrices.

$$\lambda = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}$$

$$K = \begin{bmatrix} K_1 & 0 & 0 \\ 0 & K_2 & 0 \\ 0 & 0 & K_3 \end{bmatrix}$$

SMC Results: Sans disturbance

SMC Results: Sans disturbance

SMC Results: Sans disturbance

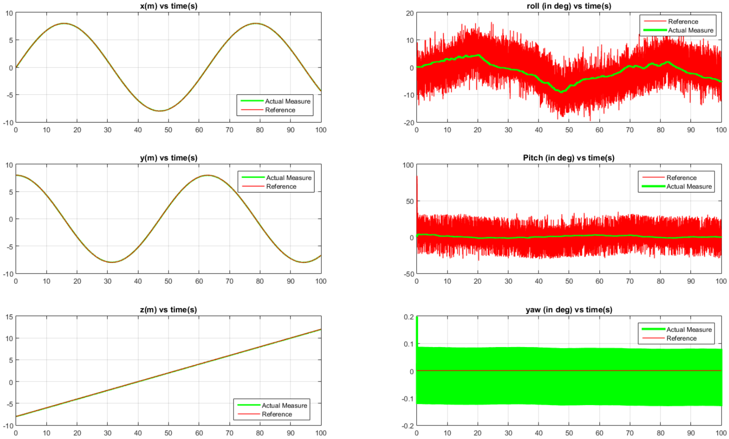

Figure 13: Position and Orientation vs Time

SMC Results: Sans disturbance

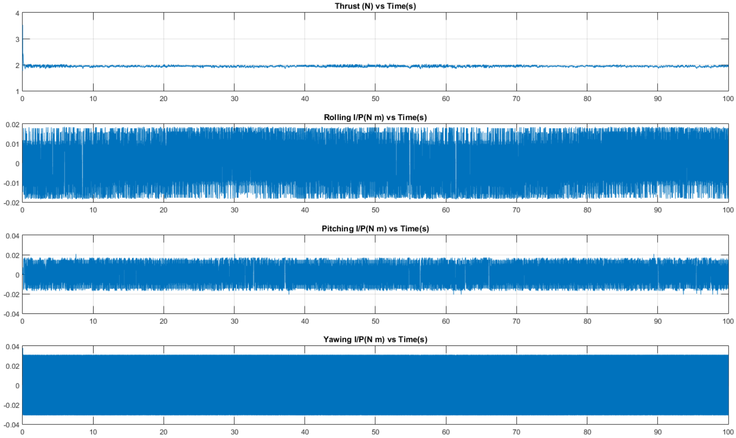

Figure 14: Thrust, Rolling, Pitching and Yawing Inputs vs Time

SMC Results: Sans disturbance

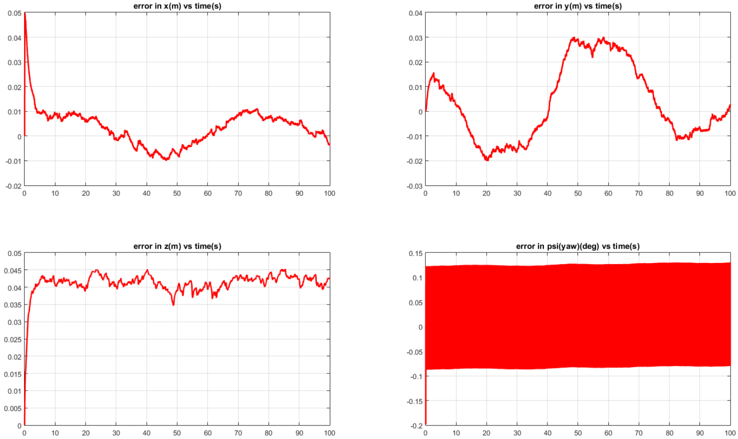

Figure 15: Errors in x,y,z and yaw

SMC Results: With disturbance

SMC Results: With disturbance

SMC Results: With disturbance

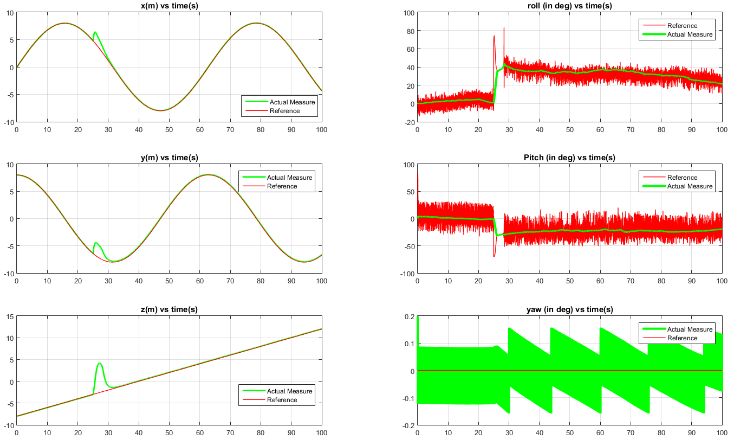

Figure 16: Position and Orientation vs Time [With Disturbance at 25s]

SMC Results: With disturbance

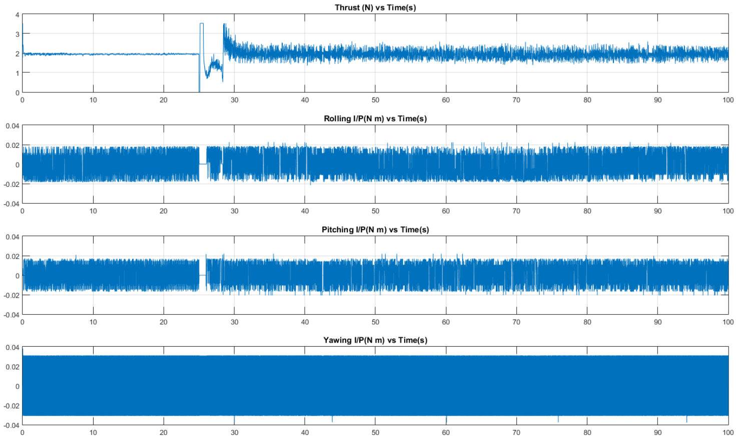

Figure 17: Thrust, Rolling, Pitching and Yawing Inputs vs Time [With Disturbance at 25s]

SMC Results: With disturbance

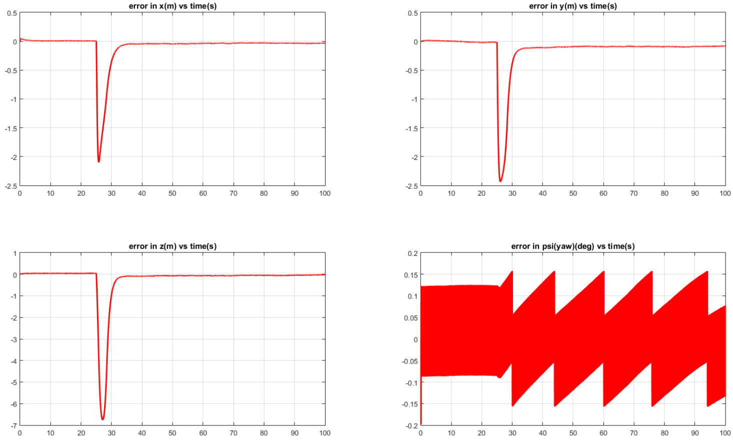

Figure 18: Errors in x,y,z and yaw [With Disturbance at 25s]

SMC: Points to note

- Without any disturbance, the tracking by SMC control is better than PD control. The magnitudes of errors is lesser than the case of PD control. But the control is discontinous and switches very frequently. The Figures 13, 14 and 15 show that the positions, orientations, control inputs and the tracjectory error in the absense of disturbances.
- The Figures 16, 17, 18 show the positions, orientations, control inputs and the tracjectory error in the presence of disturbances. It can be concluded from the plots that the control is robust enough to tolerate the effect of winds. The system becomes unstable with the addition of wind but gains control in approximately 5 seconds and all the coordinates converge to the desired values.

SMC: Conclusion

The advantages of Sliding Mode Control(SMC) are:

a. Easy to understand and implement.
b. Robust to parameter variations and disturbances.

The disadvantages of SMC are:

a. The control law is discontinuous and this may adversely affect the actuators.
b. The gains are very high and it can cause actuator saturation.

Outline

BSC

- Recursive control algorithm
- Works by designing intermediate control laws for some of the state variables.
- Does not cancel the non-linearities in the system, since some of the non linear terms can contribute to the stability of the system.

BSC

The dynamic model is re-written for the sake of convenience. The state vairables are renamed as follows: $x_1 = \phi$, $x_2 = \dot{x}_1$, $x_3 = \theta$, $x_4 = \dot{x}_2$, $x_5 = \psi$, $x_6 = \dot{x}_5$, $x_7 = z$, $x_8 = \dot{z}$, $x_9 = x$, $x_{10} = \dot{x}_9$, $x_{11} = y$ and $x_{12} = \dot{x}_{11}$.
The control inputs are:

1. Thrust$=u_1$
2. Rolling Input$=u_{21}$
   Pitching Input$=u_{22}$
   Yawing Input$=u_{23}$

The following parameters are used: $a_1 = \frac{I_{yy}-I_{xx}}{I_{xx}}$, $a_2 = \frac{I_{zz}-I_{xx}}{I_{yy}}$, $a_3 = \frac{I_{xx}-I_{yy}}{I_{zz}}$, $b_1 = \frac{1}{I_{xx}}$, $b_2 = \frac{1}{I_{yy}}$ and $b_3 = \frac{1}{I_{zz}}$.

Using these state variables and the parameters, the dynamic model can be written as:

$$
\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \\ \dot{x}_7 \\ \dot{x}_8 \\ \dot{x}_9 \\ \dot{x}_{10} \\ \dot{x}_{11} \\ \dot{x}_{12} \end{bmatrix} = \begin{bmatrix} x_2 \\ a_1 x_4 x_6 + b_1 u_{21} \\ x_4 \\ a_2 x_2 x_6 + b_2 u_{22} \\ x_6 \\ a_3 x_2 x_4 + b_3 u_{23} \\ x_8 \\ -g + b_4(\cos x_1 \cos x_3) u_1 \\ x_{10} \\ b_4(\cos x_5 \sin x_3 + \sin x_5 \cos x_3 \sin x_1) u_1 \\ x_{12} \\ b_4(\sin x_5 \sin x_3 - \cos x_5 \cos x_3 \sin x_1) u_1 \end{bmatrix} \tag{18}
$$

BSC: Roll Controller

The states x_1 and x_2 are the roll and its rate of change.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} x_2 \\ a_1 x_4 x_6 + b_1 u_{21} \end{bmatrix} \tag{19}$$

A simple positive definite Lyapunov Function is picked:

$$V_1 = \frac{1}{2} z_1^2 \tag{20}$$

where: $z_1 = x_{1c} - x_1$

$$\dot{V}_1 = z_1 \dot{z}_1 = z_1(\dot{x}_{1c} - \dot{x}_1) = z_1(\dot{x}_{1c} - x_2) \tag{21}$$

A positive definite bounding function is picked which is an bound on $\dot{V}_1$ as given in Equation 22

$$\dot{V}_1 = z_1(\dot{x}_{1c} - x_2) \leq -c_1 z_1^2 \tag{22}$$

BSC: Roll Controller

c_1 is a positive constant. To satisfy inequality 22 the virtual control input is chosen to be:

$$(x_2)_{desired} = \dot{x}_{1c} + c_1 z_1 \tag{23}$$

Rewriting Equation 21

$$\begin{aligned} &\dot{V}_1 = z_1 \dot{z}_1 = z_1(\dot{x}_{1d} - x_2) = z_1(\dot{x}_{1d} - (z_2 + \dot{x}_{1d} + c_1 z_1)) \\ \Rightarrow &\dot{V}_1 = -z_1 z_2 - c_1 z_1^2 \end{aligned} \tag{24}$$

The next step is to augment the first Lyapunov function V_1 with a quadratic term in the second variable z_2 to get a positive definite V_2.

$$\begin{aligned} &V_2 = V_1 + \frac{1}{2} z_2^2 \\ \Rightarrow &\dot{V}_2 = \dot{V}_1 + z_2 \dot{z}_2 \\ \Rightarrow &\dot{V}_2 = -z_1 z_2 - c_1 z_1^2 + z_2(\dot{x}_2 - \ddot{x}_{1c} - c_1 \dot{z}_1) \end{aligned} \tag{25}$$

BSC: Roll Controller

Choosing a positive definite bounding function and substituing the model ($\dot{x}_2$) into 25 leads to the following:

$$-z_1 z_2 - c_1 z_1^2 + z_2(a_1 x_4 x_6 + b_1 u_{21} - \ddot{x}_{1d} - c_1 \dot{z}_1) \leq -c_1 z_1^2 - c_2 z_2^2 \quad (26)$$

Using the equality case of Equation 26, we get:

$$u_{21} = \frac{1}{b_1}(\ddot{x}_{1d} + c_1 \dot{z}_1 - a_1 x_4 x_6 + z_1 - c_2 z_2) \quad (27)$$

Equation 27 is the controller output for tracking the commanded roll angle. The required pitch, yaw and the altitude can also be tracked using the same design methodology that is followed for the roll angle. The controller out outs are presented in the next slide.

BSC: Pitch, Yaw and Altitude Control Laws

- Pitch Control:

$$u_{22} = \frac{1}{b_2}(\ddot{x}_{3d} + c_3\dot{z}_3 - a_2x_2x_6 + z_3 - c_4z_4) \tag{28}$$

- Yaw Control:

$$u_{23} = \frac{1}{b_3}(\ddot{x}_{5d} + c_5\dot{z}_5 - a_3x_2x_4 + z_5 - c_6z_6) \tag{29}$$

- Altitude Control:

$$u_1 = \frac{1}{b_4 \cos x_1 \cos x_3}(\ddot{x}_{7d} + c_7\dot{z}_7 - c_8z_8 + g + z_7) \tag{30}$$

BSC Results: Sans disturbance

BSC Results: Sans disturbance

BSC Results: Sans disturbance

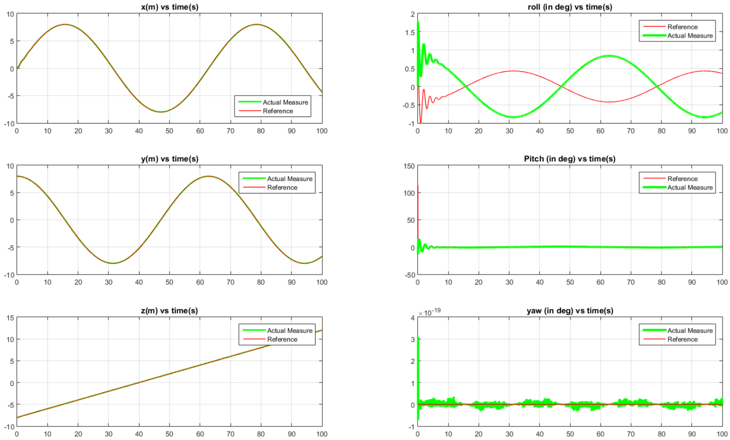

Figure 19: Position and Orientation vs Time

BSC Results: Sans disturbance

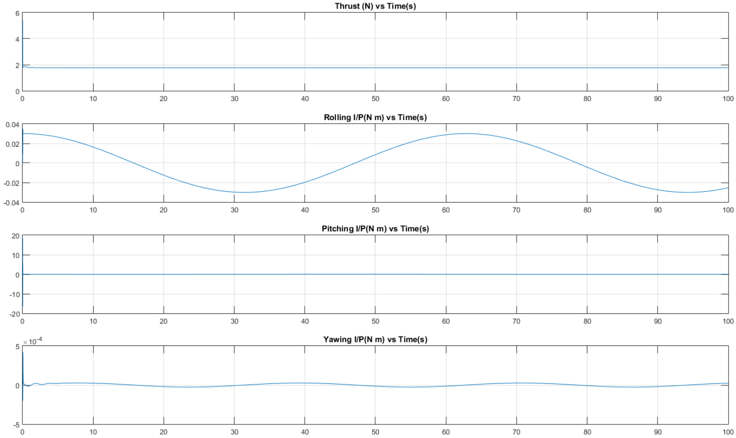

Figure 20: Thrust, Rolling, Pitching and Yawing Inputs vs Time

BSC Results: Sans disturbance

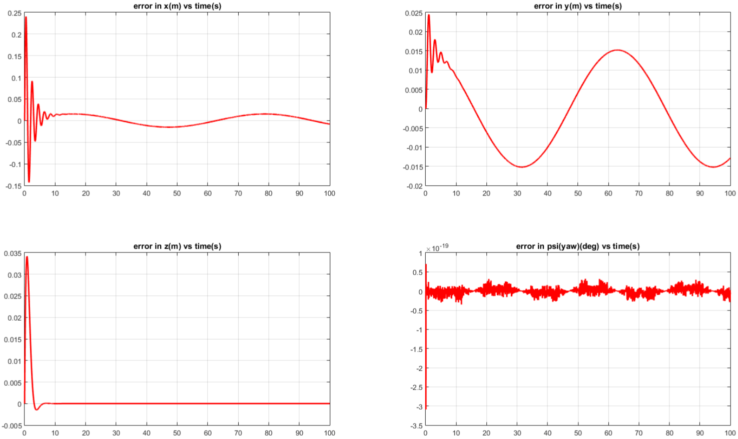

Figure 21: Errors in x,y,z and yaw

BSC Results: With disturbance

BSC Results: With disturbance

BSC Results: With disturbance

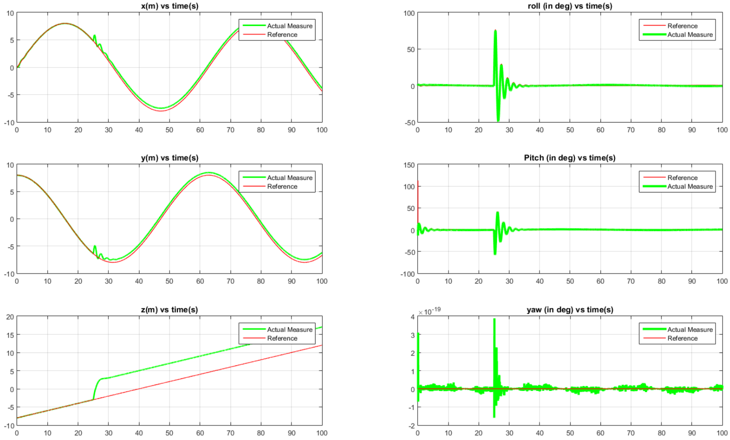

Figure 22: Position and Orientation vs Time [With Disturbance at 25s]

BSC Results: With disturbance

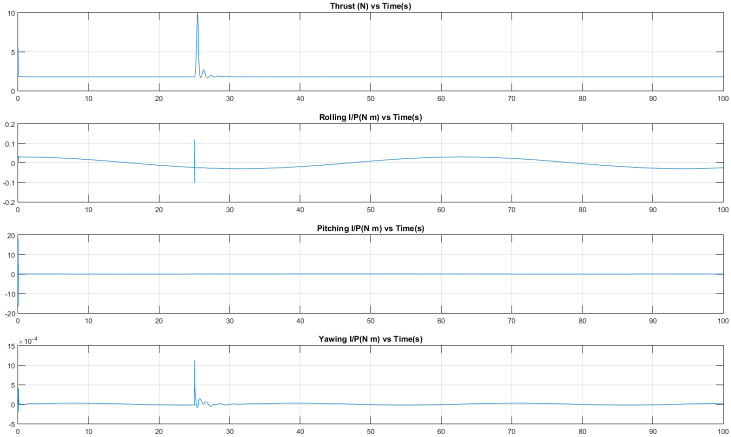

Figure 23: Thrust, Rolling, Pitching and Yawing Inputs vs Time [With Disturbance at 25s]

BSC Results: With disturbance

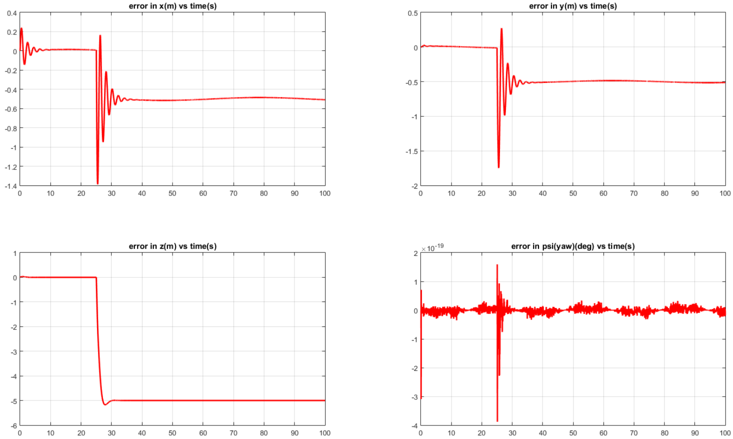

Figure 24: Errors in x,y,z and yaw [With Disturbance at 25s]

BSC: Points to note

- Without any disturbance, the tracking by Backstepping Control is better than both Proportional Derivative and Sliding Mode Control. The magnitudes of errors is the least. The control is smooth and continous. The Figures 19, 20, 21 show the positions, orientations, control inputs and the tracjectory error in the absense of disturbances.
- The Figures 22, 23, 24 show the positions, orientations, control inputs and the tracjectory error in the presence of disturbances. It can be concluded from the plots that the control does not perform as well as SMC, there is significant steady state error and the system does not converge to the desired trajectory but has steady state errors. The system does not become unstable with but does not converge to the desired values either.

BSC: Conclusion

The advantages of Backstepping Control(BSC) are:

a. Ensures Lyapunov Stability.
b. It does not involve cancelling of system non-linearities by feedback linearization.

The disadvantages of BSC are:

a. The theory is mathematically exacting.
b. There are a number of gains to tune.
c. Although it does not become unstable with introduction of disturbances, there is considerable finite steady state error. The solution can be to use integral backstepping.

Conclusion

[Disturbance/Control]	$max\|e_x\|(m)$	$max\|e_y\|(m)$	$max\|e_z\|(m)$	$max\|e_\psi\|(\text{deg})$	Control
Without Disturbance/PD	0.0747	0.0747	0	0.016	Low and Smooth
Without Disturbance/SMC	0.01	0.03	0	0.123	Discontinous
Without Disturbance/BSC	0.0151	0.0151	0	0	Low and Smooth
With Disturbance/PD	∞	∞	0	∞	Saturated
With Disturbance/SMC	0.03	0.08	0.06	0.15	Discontinous
With Disturbance/BSC	0.5	0.5	5	0	Low and Smooth

Table 1: Comparison Table

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Thank You!