Observer based Anti-windup technique for Twin Rotor MIMO System

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Abstract. Necessary control techniques must be used in control systems for their proper and smooth operation even in the case of uncertainties and disturbances like sensor-actuator failure. The TRMS workshop serves as a simplified model of a helicopter retaining most of the important dynamic characteristics and cross coupling. This project aims to solve the problem of synthesizing anti-windup control technique based on observer to avoid controller signal entering into saturation in TRMS. The effects of saturation is that systems experience Integrator wind-up. Once the input saturates, the integral of the error keeps increasing. Any further change in the input does not lead to any change of the output of the saturated component. The system behaves like an open-loop configuration, and no control is available. The project applies a Sliding mode control algorithm to the TRMS and uses an observer as an anti-windup technique so that the system doesn’t cease to work even in the case of sensor failure. Using this scheme, the entire system of TRMS along with sensor failure was tested by giving step inputs and the outputs, pitch and yaw were obtained. The results obtained indicated that even in the presence of uncertainties, the system was able to track the given step input without going unstable.

Keywords: TRMS, anti-windup, sensor-actuator failure, sliding mode controller, observer

1. Introduction
The modelling dynamics of aircrafts is often troublesome due to the coupling effect between the rotors, nonlinear behavior and unavailability of system states. Twin rotor multi-input multi-output system is a in vitro setup designed for control experiments, which resembles a helicopter but with necessary changes. It has unstable, nonlinear, and coupled dynamics. The project focuses on the design and analysis of sliding mode control (SMC) algorithm for pitch and yaw angle control of main and tail rotor of the TRMS under parametric uncertainty along with Observer based anti-windup (AW) technique to mitigate the consequences of actuator limitations on the performance and stability of the controlled system as actuator saturation induces a windup phenomenon and potentially results in system instability. The laboratory setup is utilized readily, which resembles a helicopter but with some significant assumptions being made to make our work easier. Yet the most important dynamic characteristics are captured in the TRMS model like the cross coupling between two rotors[4]. Considering the voltages supplied to the rotors as two inputs, vertical and horizontal angles and angular velocities are obtained as outputs. The TRMS can be controlled by yaw control and pitch control similar to helicopter which is two Degree of freedom (DOF). The yaw controls the horizontal movement i.e. left and right motion
of tail rotor of TRMS whereas pitch controls the horizontal movement. The source voltages of the DC motors (main ($u_m$) and tail ($u_t$)) are control inputs. In order to control TRMS in a desired way, the speed of rotors is altered, whereas in helicopter it is done by changing the angles of rotors. The cross coupling between two planes of motion impacts the beam velocity in each plane which occurs due to the rotation of the propeller. The measurable output states of the system are pitch and yaw. These states are to be controlled via control algorithms in order to keep the system stable. The bound for the control signal is set to $[-2.5V \ldots +2.5V]$. The control algorithm used in the project is the Sliding Mode Control (SMC). SMC is a nonlinear control technique that alters the dynamics of a nonlinear system by application of a discontinuous control signal that forces the system to "slide" along a cross-section of the system's normal behavior. The vital characteristic of SMC is its insensitivity to parametric uncertainty and external disturbances during sliding mode. Moreover, it accredits the decoupling of the lower dimensions, and consequently, it scales down the complication of feedback design. The technique in which the effects of saturation are tried to be nullified is called anti-windup. The main effect being Integral windup where the large integral value prevents the controller from resuming normal operations quickly thus delaying the response.

2. Materials and Methods

2.1 Linearized modelling of TRMS in state space

The state space equation of non-linear system obtained from paper [1] is considered as the base for deriving at linearized model of TRMS. The non-linear system is linearized after taking Jacobean matrices and putting point (0, 0), and substituting the values of the constants.

The state space equations of linearized model are as follows:

$$x_1 = x_2$$
$$x_2 = -4.7059x_1 - 0.0882x_2 + 1.3588x_5$$
$$x_3 = x_4$$
$$x_4 = -5x_4 + 1.619x_5 + 4.5x_6$$
$$x_5 = -0.9091x_5 + u_1$$
$$x_6 = -1.25x_6 + u_2$$

The state, output vectors are

$$x = [x_1 \ x_3 \ x_5 \ x_6]^T$$
$$y = [x_1 \ x_3]^T$$

Where

$x_1$: Pitch (elevation) angle
$x_3$: Yaw (azimuth) angle
$x_5$: Momentum of main rotor
$x_6$: Momentum of tail rotor

The six state variables chosen are pitch, yaw, first derivatives of pitch and yaw, and angular velocities of main and tail rotors. Pitching and Yawing are the two measurable states that have to be controlled. The inputs to the system are DC voltages to the main($u_1$) and tail ($u_2$) rotors which control the system.
2.2 Sliding Mode Control
SMC is applicable in nonlinear system, multi-input multi-output (MIMO) systems, discrete-time models, large-scale and infinite dimension systems. SMC comprises of high-speed switching control law which brings the states of nonlinear plants to a user-defined sliding or switching surface and retains the states on this surface then on. SMC usually consist of two phases: reaching phase and the sliding phase. The reaching phase converges the system states to desired surface. The sliding phase handles the oscillations [1]. The two key advantages of sliding mode control: firstly, the dynamic behavior of the system may be tailored by the particular choice of the sliding function. Secondly, the closed loop-response becomes totally insensitive to some particular uncertainties like model parameter uncertainties, disturbance and nonlinearity that are bounded. From a practical point of view SMC allows for controlling nonlinear processes subject to external disturbances and heavy model uncertainties.

For Pitch loop:
Sliding surface \( s_1 = \dot{\theta} + c_1 \dot{\theta} + c_0 \theta \) (2.9)
Control law \( u_1 = \text{sign}(s_1) \) (2.10)
Where error in pitch loop
\( e = \text{ref} - x_1 \) (2.11)

For Yaw loop:
Sliding surface \( s_2 = \dot{\psi} + c_2 \dot{\psi} + c_3 \psi \) (2.12)
Control law \( u_2 = \text{sign}(s_2) \) (2.13)

|             | Pitch in rad | Yaw in rad |
|-------------|--------------|------------|
| Case 1      |              |            |
|             | \( c_0 = 0.818 \) | \( c_2 = 10 \) |
|             | \( c_1 = 1.85 \) | \( c_4 = 7 \) |
| Slider gain | 27.65        | Slider gain = |
|             |              | 23.041     |
| Case 2      |              |            |
|             | \( c_0 = 0.818 \) | \( c_2 = 10 \) |
|             | \( c_1 = 1.6 \) | \( c_4 = 7 \) |
| Slider gain | 18.24        | Slider gain = |
|             |              | 32.25      |

Table 2.1: Values of tuning parameters for SMC
In the presence of saturation block, the sliding surface equation remains the same and control law equation of SMC controller modifies to:

For pitch loop, control law ($u_1$)

$$u_1 = \text{sign}(s_1) - e_2$$

(2.14)

Where, $e_2 = \text{sat}(U) - U$

(2.15)

$U$ is the controller output and $s_1$ is the sliding surface of pitch loop

For yaw loop, control law ($u_2$)

$$u_2 = \text{sign}(s_2) - e_2$$

(2.16)

Where, $e_2 = \text{sat}(U_1) - U_1$

(2.17)

$U_1$ is the controller output and $s_2$ is the sliding surface of yaw loop

2.3 Observer Based Anti-Windup

The observer chosen is the Extended Kalman (EK) based observer. The simple estimating and correcting mechanisms of Kalman filter is used in design of observers. Extended Kalman filter is used as the estimation algorithm in the observer system because it minimizes the variance of the error between actual and estimated states[3]. Kalman filtering is a well renowned technique used in control system as predictor plus corrector.

![Fig 2.1. TRMS plant with control signal saturation and anti-windup technique](image)

The above figure represents the system model which was rigged up on Simulink used to simulate the observer based anti-windup technique. Step inputs are provided to the system and then the error signal is computed by subtracting it with the output from the sensor failure block. The output of both these adders is now given to a saturation block which has already been specified just streamlines the oncoming input.

$$\text{sat}(u) = \begin{cases} 
    u_{\text{max}} & \text{if } u \geq u_{\text{max}} \\
    u & \text{if } u_{\text{min}} \leq u \leq u_{\text{max}} \\
    u_{\text{min}} & \text{if } u \leq u_{\text{min}}
\end{cases}$$

The output of this block is in turn directed to the sliding mode controller and the output of the sensor failure is either $x_1$ or $x_1h$ for the pitch block whereas $x_3$ or $x_3h$ for the yaw block. When a failure occurs, the expected state, the $h$ state is sent out as an output. This state has been calculated with the help of the observer block in the system. If no failure
occurs, the normal states are sent out as outputs. Looking into the next main component of the system Simulink block, the observer block. This block is an integral cog in the anti-windup scheme. This block helps us tend to the uncertainties existing in the real world, a prime example being sensor failure. The observer block acts as a fail-safe for the existing TRMS setup. The expected states of the system are simultaneously calculated in the observer block and when a failure occurs the calculated states are supplied as inputs to the system as the output from the original system tends to be erroneous.

3. Result and Discussion

Case 1: TRMS simulation with Sliding Mode Controller

![Simulink block of TRMS with SMC](image1)

![Pitch output of TRMS with SMC](image2)

![Yaw output of TRMS with SMC](image3)

The above Fig. 3.2 and Fig. 3.4 show the closed loop Pitch and Yaw outputs of TRMS along with SMC. Both pitch and yaw references are 1 radians. Fig 4.3 and Fig. 4.5 show the pitch and yaw controller outputs of TRMS with SMC respectively. Average value of pitch controller output is 0.0495V and yaw controller output is -0.0693V. The pitch and yaw follow the control signal and hence there is no problem.

Case 2: TRMS with sensor failure

![Simulink block of TRMS with sensor failure](image4)

![Pitch output of TRMS](image5)

![Yaw output of TRMS](image6)

Average value of controller output before sensor failure is 0.05 whereas average value of controller output after sensor failure is 1. After sensor failure, the pitch and yaw output goes out of bounds, the controller goes to saturation, thus implying the need for anti-windup technique. In the absence of observer, the responses reflect that the control action is
affected causing instability under failures of sensors at 40 seconds. Hence there is a necessity of integrating an observer along with control which enables the system to provide smooth performance under sensor failure.

**Case 3: EK observer based SMC with saturation and sensor failure**

![Simulink block of TRMS with EK observer based SMC with saturation component and sensor failure](image)

**Fig 3.7. Simulink block of TRMS with EK observer based SMC with saturation component and sensor failure**

![Pitch of TRMS with EK observer based SMC](image)

![Yaw of TRMS with EK observer based SMC](image)

**Fig 3.8. Pitch of TRMS with EK observer based SMC**  **Fig 3.9. Yaw of TRMS with EK observer based SMC**

To offset the effects of the Sensor failure block we bring in the Observer. It acts as a fail-safe by estimating the states of the system and when a failure occurs, it steps in for the system and tracks the given step input. In the absence of an observer based anti-windup technique, the system would have gone into saturation and the controller would have stopped working. This is prevented by using the observer based anti-windup technique. Hence, both the pitch and yaw output remain within bounds.
4. Conclusion

This project obtains the linear state space model for Twin rotor MIMO system (TRMS). The six state variables had been identified as pitch, yaw, their respective first derivatives and main and tail rotor angular velocities. The measurable outputs, pitch and yaw have been the states to be controlled. SMC technique have been discussed and employed to the system. As it can be seen from the above closed loop responses of no failure and sensor failure cases, there is a pressing need for an Anti-windup scheme to account for the uncertainties pertaining to the system, namely sensor failures. The sensor failure which has been applied around 40 seconds makes both the outputs of the TRMS go to instability as the controller output goes to saturation leading to actuator not to perform its prescribed work. Hence to obtain stable and required performance from TRMS, incorporating an observer along with advanced control algorithms is a guaranteed feasible solution. The observer is used as an anti-windup technique, which basically employs the difference between the controller’s input and output. This technique as it has been found has a lot of advantages, it prevents the system from entering into an unstable region, acts as a fail-safe when the system encounters some kind of failure and furthermore it helps track the given step input even in the case of uncertainties. Hence, this observer based anti-windup technique can be used as a reliable method to keep the system in the stable region even in the presence of uncertainties.

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