Controller and Observer Techniques for Twin Rotor MIMO System

Tejas S. Jadhav, Swapnil Y. Gadgune

Abstract: ***This paper elaborates the controller and observer system with all mathematical modeling of Twin Rotor MIMO System (TRMS) which is eminently nonlinear system. TRMS is 2 DOF (Degree of Freedom) helicopter model which originated in company called Feedback Instrument Limited for controlling and experimenting of different algorithms. Two DOFs i.e. Yaw and Pitch control need to control by using controller, that imply to track a desired path. Nowadays, the Unmanned Aerial Vehicles (UAV) has been tremendously useful for road traffic by video surveillance and supervisions for public purposes. Because of capacity to hover, helicopters can be used in any environmental conditions. Hence, Scope of TRMS studies has been increasing.***

Keywords: MIMO; TRMS; FUZZY Controller; SMC Controller.

I. INTRODUCTION

The Twin Rotor MIMO system is a prototype of flight control helicopter model with 2 Degree of Freedom (DOF). The resemblance of UAV and TRMS leads more interest in control of TRMS these days. It has two rotors i.e. horizontal and vertical, whose positions to be controlled by using suitable controller. Unlike in real helicopter, TRMS position controls through the rotor velocity variation.It has some problem which should be in account of controlling of TRMS that the TRMS eminently nonlinear multi input multi output (MIMO) system with considerable cross coupling effect between the main rotor and tail rotor. That imply the inaccessible number states and their outputs are present which cannot measurable.

II. TWIN ROTOR MIMO SYSTEM

Experimental setup of TRMS is flight control helicopter system which has two propellers which is perpendicular to each other. TRMS consists of two motor one at front known as main rotor and second at tail known as tail rotor. Rotors are connected by beam pivoted at the base in same manner where it can move around in horizontally and vertically both ways.

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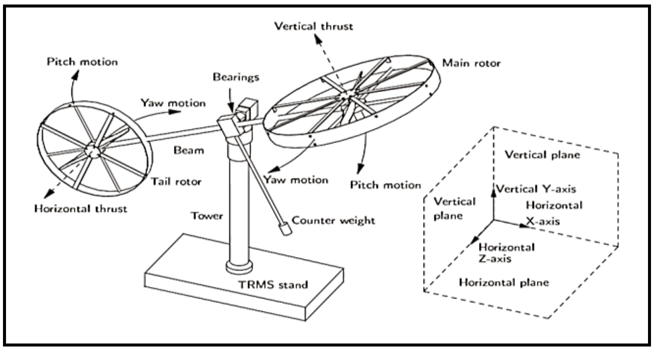

Fig (a): TRMS

The function of main motor is for up and down movement whereas the tail rotor is used for clockwise or anticlockwise rotation of TRMS. The power to motor is given through slip rings. The tail rotor has force to move beam horizontally (yaw angle) and main rotor has raising force to move beam to vertically upward and downward (pitch angle). Aerodynamic force occurred through blades by motor with significant cross coupling in between them. A counter weight is attached fixed at pivot of beam to counterbalance and that maintain stability. At the end of beam, two ideal dc motors are connected to drive rotor and tachogenerator is used to measure angular velocities of motor.

Angle of attack is fixed in TRMS whereas in helicopters the aerodynamic exerted forces are controlled by variation of angle of attack. Following are equation of mathematical modelling of highly nonlinear TRMS:

The equation for main rotor is mentioned below from (1) to (6),

$$l_1 . \alpha''_v = M_1 - M_{FG} - M_{B\alpha_v} - M_G \tag{1}$$

Where, the M_1 is nonlinear static characteristic,

$$M_1 = \alpha_1 . \tau_1^2 + b_1 . \tau_1 \tag{2}$$

M_{FG} is a Gravity momentum,

$$M_{FG} = M_g . \sin\alpha_v \tag{3}$$

$M_{B\alpha_v}$ is Friction force momentum

$$M_{B\alpha_v} = B_{1\alpha_v} . \alpha'_v - \frac{0.0326}{2} \sin 2\alpha_v . \alpha'_h \tag{4}$$

And M_G is gyroscopic momentum

$$M_G = k_{gy} . M_1 . \dot{\alpha}_h . \cos\alpha_v \tag{5}$$

The transfer function of main motor in Laplace domain is as below:

$$\tau_1 = \frac{k_1}{T_{11}s + T_{10}} . v_u \tag{6}$$

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Table 1.1 Notations of TRMS

Sym.	Description of Parameters	Value
l_1	Moment of inertia of vertical rotor	0.068 $kg\ m^2$
l_2	Mom. of inertia of horizontal rotor	0.02 $kg\ m^2$
a_1, a_2	Static characteristic	0.0135 ,0.02
b_1, b_2	Static characteristic	0.0294,0.09 m
Mg	Gravity momentum	0.32 N m
$B1\alpha_v$	Friction momentum function	0.006 N-m-s/rad
$B1\alpha_h$	Friction momentum function	0.1 N-m-s/rad
k_{gy}	Gyroscopic momentum parameter	0.0155 s/rad
k_1	Main rotor gain	1.1
k_2	Tail rotor gain	0.8
T_{10}, T_{11}	Main rotor denominator	1, 1.1
T_{20}, T_{21}	Tail rotor denominator	1 ,1
T_p, T_0	Cross reaction Momentum parameter	2 , 3.5
k_c	Cross reaction momentum gain	-0.2

The equation for tail rotor is mentioned below from (7) to (12).

The momentum expression for the horizontal system

$$l_2 . \ddot{\alpha}_h = M_2 - M_{B\alpha_h} - M_R \tag{7}$$

Where, the M_2 is nonlinear static characteristic

$$M_2 = a_2 . \tau_2^2 + b_2 . \tau_2 \tag{8}$$

$M_{B\alpha_h}$ is friction forces momentum

$$M_{B\alpha_h} = B_{1\alpha_h} . \dot{\alpha}_h \tag{9}$$

And MR is the cross reaction momentum is shown as

$$M_R = \frac{K_c(T_0 s+1)}{(T_p s+1)} . M_1 \tag{10}$$

Applying inverse Laplace transform on equation (10), it will be

$$M_R = \frac{K_c T_0}{T_p} . M_1 \tag{11}$$

The transfer function of tail motor in Laplace domain is as below:

$$\tau_2 = \frac{K_2}{T_{21}s + T_{20}} . u_h \tag{12}$$

Combining all above equation (1 - 12) in state space form as follows:

$$\frac{d\alpha_v}{dt} = \dot{\alpha}_v$$

$$\frac{d\dot{\alpha}_v}{dt} = \frac{a_1}{I_1}\tau_1^2 + \frac{b_1}{I_1}\tau_1 - \frac{M_g}{I_1} sin\alpha_v - \frac{B_{1\alpha_v}}{I_1}\dot{\alpha}_v + \frac{0.0326}{2I_1}\sin(2\alpha_v)\,\dot{\alpha}_h^2 - \frac{k_{gy}}{I_1} a_1 \cos(\alpha_v)\,\dot{\alpha}_h \tau_1^2 - \frac{k_{gy}}{I_1} b_1 \cos(\alpha_v)\,\dot{\alpha}_h \tau_1$$

$$\frac{d\alpha_h}{dt} = \dot{\alpha}_h$$

$$\frac{d\dot{\alpha}_h}{dt} = \frac{a_2}{I_2}\tau_2^2 + \frac{b_2}{I_2}\tau_2 - \frac{B_{1\alpha_h}}{I_1}\dot{\alpha}_h - -\frac{k_c}{I_2} a_1 1.75 \tau_1^2 - \frac{1.75}{I_1} b_1 k_c \tau_1$$

$$\frac{d\tau_1}{dt} = \frac{T_{10}}{T_{11}}\tau_1 + \frac{k_1}{T_{11}} u_v$$

$$\frac{d\tau_2}{dt} = \frac{T_{20}}{T_{21}}\tau_1 + \frac{k_2}{T_{21}} u_h \tag{13}$$

The above variables can be converted into state variable format as

$x_1 = \alpha_v$, pitch angle

$x_3 = \alpha_h$, yaw angle

$x_2 = \Omega_v$, pitch angular velocity in the vertical plane

$x_4 = \Omega_h$, yaw angular velocity in the horizontal plane

$x_5 = \tau_1$, momentum of main motor

$x_6 = \tau_2$, momentum of tail motor

After putting the state variables, it gets

$$\frac{dx_1}{dt} = x_2$$

$$\frac{dx_2}{dt} = \frac{a_1}{I_1}x_5^2 + \frac{b_1}{I_1}x_5 - \frac{M_g}{I_1} sinx_1 - \frac{B_{1\alpha_v}}{I_1}x_2 + \frac{0.0326}{2I_1}\sin(2x_2)\,x_4^2 - \frac{k_{gy}}{I_1} a_1 \cos(x_1)\,x_4 x_5^2 - \frac{k_{gy}}{I_1} b_1 \cos(x_1)\,x_4 x_5$$

$$\frac{dx_3}{dt} = x_4$$

$$\frac{dx_4}{dt} = \frac{a_2}{I_2}x_6^2 + \frac{b_2}{I_2}x_6 - \frac{B_{1\alpha_h}}{I_2}x_4 - -\frac{k_c}{I_2} a_1 1.75 x_5^2 - \frac{1.75}{I_2} b_1 k_c x_5$$

$$\frac{dx_5}{dt} = -\frac{T_{10}}{T_{11}}x_5 + \frac{k_1}{T_{11}} u_v$$

$$\frac{dx_6}{dt} = -\frac{T_{20}}{T_{21}}x_5 + \frac{k_2}{T_{21}} u_h \tag{14}$$

There are several techniques implemented on TRMS. One of the most common methods of controlling is through PID controller. But there are other several methods are invented which can control the TRMS and conquer the disadvantages made by PID controller. The TRMS system is divided into TRMS-horizontal and TRMS-vertical by decoupled for simplification of complexity [1]. Following are the controllers which can be used for controlling of TRMS.

III. PID CONTROLLER

PID control method is very oldest method and helpful of controlling which has been created in 17th century. It has good performance on TRMS but only concern is high level nonlinearity and complexity of TRMS. Nowadays some new techniques are collaborated with PID. The tuning of PID for particular output and which cannot further controlled continuously are the drawback of PID which can be eliminated with help of some new technique collaborated with PID.

Simple PID for vertical and horizontal of TRMS

To elimination of complexity, the TRMS is integrated into two systems vertical and horizontal [1]. The simple PID can be separately tuned for Yaw and Pitch and in that only1- DOF system is considered [4]. After tuning the PID at the particular value, the TRMS output will trace a desired path.

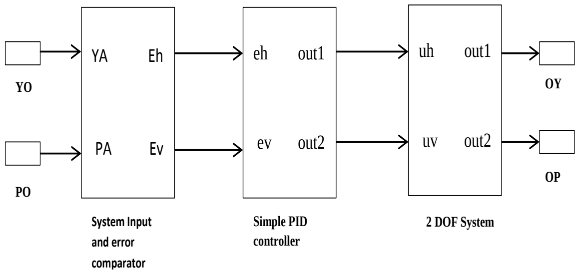

Fig (b): Simple PID for yaw and pitch control separately

A. Cross coupling PID for 2 DOF TRMS

In 2 DOF TRMS system, the cross coupling effect takes place. This means, nature of TRMS is highly nonlinear and complex, vertical and horizontal systems interfere with each other. This is one of concern in TRMS which can be solved by use of PID in cross coupling manner. In [6], the arrangement of PID is shown. Thus, the controlling of TRMS can be done by using PID controller.

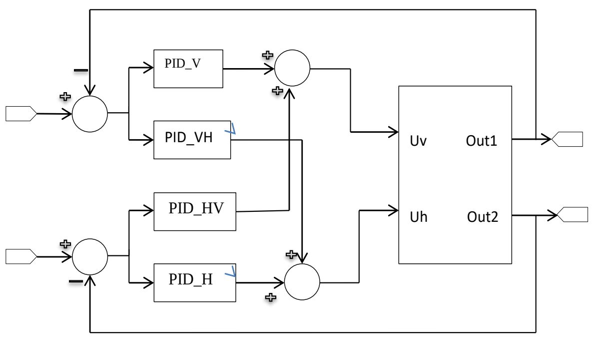

Fig (c): Cross coupling of PID for Yaw and Pitch control simalenously

B. PID with derivative filter method

In [5], two PID is used simultaneously with derivative filter (N). It can locate the pole of filter in derivative which to reduce controller sensitivity. Equation for PID controller is shown as,

$$u(t) = Kpe(t) + Ki\int e(t).dt + Kd\,\frac{de(t)}{dt}$$
$$G(s) = Kp + Ki/s + Kd * s$$
$$G(s) = Kp + \frac{Ki}{s} + Kd * \left(\frac{Ns}{N+S}\right)$$
$$D = \frac{S*Kp*td}{1+s*\frac{td}{N}} \qquad (15)$$

IV. SLIDING MODE CONTROLLER

SMC is useful method of controlling which can slide on cross section of desired surface. This is known as sliding plane or surface and the technique known as SMC. The advantages of this system are it is not affected by parameter changes and also outside disturbance. It is robust in controller because of having advantages which is essential in uncertain dynamics. In [1], the sliding mode controller is designed for horizontal and vertical system.

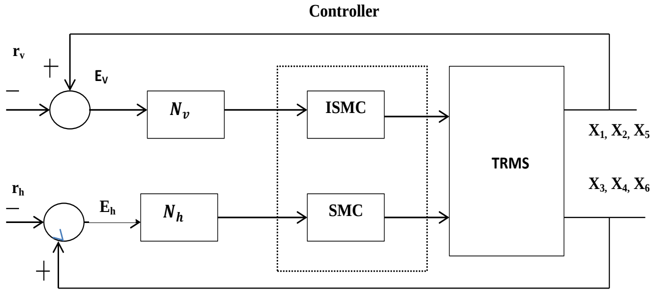

Fig (d) Sliding mode controller for TRMS

The sliding function is termed where reaching condition must be satisfied,

$$N\dot{N} < 0\,, N \neq 0 \qquad (16)$$

The designing of horizontal and vertical SMC's are separated [1]. The equation for sliding mode controller for horizontal control i. e. Yaw angle is mentioned [1]. The sliding function of TRMS-Horizontal be

$$N_h = P_{h1}e_{h1} + P_{h2}e_{h2} \qquad (17)$$

Where, $P_{h1} = [P_{h11} \quad P_{h12}]$ εR2,$P_{h11}, P_{h12} > 0$, and P_{h1} εR , $P_{h1} > 0$

Using a constant of proportional reaching law

$$\dot{N}_{h} = -\rho_{1h}\sigma_h - \rho_{2h}\sin(N_h) \qquad (18)$$

After taking derivative of equation (16), it can equate to equation (17), the output of SMC will be

$$u_h = (P_{h2}B_{h2})^{-1}P_{h1}(A_{h11}e_{h1} + A_{h12}e_{h2}) + P_{h2}(A_{h21}e_{h1} + A_{h22}e_{h2}) + \rho_{1h}N_h + \rho_{2h}\sin(N_h) \qquad (19)$$

Where, value of A_{h11}, A_{h12} , A_{h22}, A_{h21}, B_{h2} are

$$A_{h11} = \begin{bmatrix} a_{h11} & a_{h12} \\ a_{h13} & a_{h14} \end{bmatrix}, A_{h12} = \begin{bmatrix} a_{h13} \\ a_{h23} \end{bmatrix},$$

$$A_{h21} = [\,a_{h31} \quad a_{h32}\,] \quad ,A_h = \begin{bmatrix} 0 & 1 & 0 \\ 0 & \frac{-B_{1a_h}}{I_2} & \frac{B_2}{I_2} \\ 0 & 0 & -\frac{T_{20}}{T_{21}} \end{bmatrix}$$

$$,B_h = \begin{bmatrix} 0 \\ 0 \\ \frac{K_2}{T_{21}} \end{bmatrix}$$

$$A_{h22} = [a_{h33}], \qquad B_{h2} = [0 \quad b_{h31}]^T$$

The vertical control i.e. Pitch position control is done with help of Integral SMC (ISMC) is designed. The normally main propeller is larger and heavy than the tail rotor. Hence TRMS is seen asymmetric by weighs. Also Pitch angle cannot be in uncontrolled conditions. Hence, the simple SMC is not applicable to pitch control to make the zero position error and to reduce the effect of asymmetric weights at $e_{v1} = 0$, the ISMC is designed.

The equation for sliding function for TRMS-Vertical system is

$$N_v = P_{v1} e_{v1} + p_{v2} e_{v2} + P_{v3} \int e_{v1}\, dt \qquad (20)$$

Also here the constant proportionality reaching law for TRMS –vertical

$$\dot{N}_v = -\rho_{1v} \sigma_v - \rho_{2v} \sin(N_v) \qquad (21)$$

After taking derivative of equation (20), that equation can be equate to equation (21), the output of ISMC will be

$$u_v = (P_{v2} B_{v2})^{-1} (P_{v1} (A_{v11} e_{v1} + A_{v12} e_{v2}) + P_{v2} (A_{v21} e_{v1} + A_{v22} e_{v2}) + \rho_{1v} N_v + \rho_{2v} \sin(N_v)) \qquad (22)$$

Where, values of $A_{v11}, A_{v12}, A_{v21}$ and A_{v22} are

$$A_{v11} = \begin{bmatrix} a_{v11} & a_{v12} \\ a_{v13} & a_{v14} \end{bmatrix}, \quad A_{v12} = \begin{bmatrix} a_{v13} \\ a_{v23} \end{bmatrix},$$

$$A_{v21} = [\, a_{v31} \quad a_{v32}], \quad A_{v22} = [a_{v33}],$$

$$B_{v2} = [\, 0 \quad b_{v31}]^T$$

$$A_v == \begin{bmatrix} 0 & 1 & 0 \\ \frac{M_g}{I_1} & \frac{-B_{1a_v}}{I_1} & \frac{B_1}{I_1} \\ 0 & 0 & -\frac{T_{10}}{T_{11}} \end{bmatrix}, B_v = \begin{bmatrix} 0 \\ 0 \\ \frac{K_1}{T_{11}} \end{bmatrix}$$

Also the Second order Sliding Mode controller (SOSMC) can be implemented by taking the derivative of u_v and u_h. The disadvantage of SMC is chattering which can be eliminated by SOSMC. The SMC is used in electromechanical and mechanical system; its chattering problem can affect and damage the actuator because of their high frequency oscillation. In [3], the twisting algorithm is used to design the SOSMC. That whole arrangement reduces undesired chattering from the input and also the external disturbance cannot affect the yaw and pitch angles of TRMS. The equations are shown below,

$$\dot{u}_h = \begin{cases} -u_h \\ -\alpha_h sign(\dot{N}_h + \beta_h |N_h|^{\frac{1}{2}} sign(N_h)) \end{cases}$$

$$\dot{u}_v = \begin{cases} -u_v \\ -\alpha_v sign(\dot{N}_v + \beta_v |N_v|^{\frac{1}{2}} sign(N_v)) \end{cases} \qquad (23)$$

V. HYBRID PID CONTROLLER BASED ON SINGLE NEURON

These days implementing different algorithms of combination of two techniques instead of one technique are taking place. That helps to combine the advantages of different methods in one. The SMC, PID and fuzzy logic controller are most popular methods combine with different other techniques such as PID with Single neuron method, Neuro fuzzy method, SMC with fuzzy controller method and so on. These methods are tested on TRMS and the output is gathered for further analysis among different techniques.

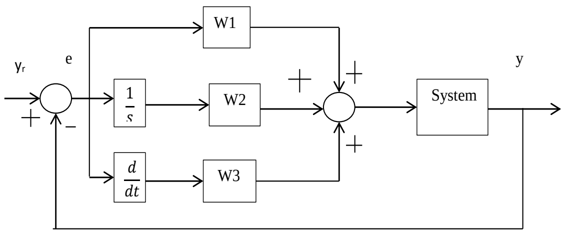

Fig (e): Hybrid PID controller using single neuron

In PID controller is designed considering single neuron method in which PID controller is shown as below. The PID controller is

$$u(k) = u(k-1) + K_p x_2(k) + K_I x_1(k) + K_D x_3(k)$$

The expression for single neuron is,

$$u(k) = u(k-1) + k \sum_{i=1}^{3} w_i(k) x_i(k), i = 1,2,3$$

Where,

$$w_i(k) = \frac{w_i}{\sum_{i=1}^{3} |w_i(k)|}$$

$$w_i(k+1) = w_i(k) + \gamma_i \,\Delta w_i(k+1) + (1 - \gamma_i) w_i(k) \qquad (24)$$

Where,

$$w_1(0) = \frac{K_{I0}}{K}, \quad w_1(0) = \frac{K_{P0}}{K}, \; w_1(0) = \frac{K_{D0}}{K}$$

Where, K_{I0}, K_{P0} and K_{D0} are the PID coefficient.

VI. T-S FUZZY MODEL BASED CONTROLLER

This Takagi –Sugeno (T-S) method is used for eminently nonlinear system which complex in behavior. Linear matrix inequality (LMI) is used to design the T-S fuzzy controller. It based on rules of linear model and membership function which is nothing but a finding a degree of membership of rule. Fuzzy method is based on the condition of “if and then”. It has set of “if and then” statements which is rules for fuzzy model and it links the input and output variables.

In [8], decoupling of TRMS is done; vertical system can be shown as:

$$x_v = [x_1 \;\; x_2 \, x_5 \, x_7]$$

The horizontal will be,

$$x_h = [x_3\ x_4\ x_6\ x_8] \quad (25)$$

That means it has eight stages but because of nonlinear behavior the some stages of them can only be measurable. This can be done by use of observer in system which explained in next section. The controller equations of this are shown below

For horizontal system,

$$u_h = -\sum_1^9 \sigma_j K_{hj} x_h(t) \quad (26)$$

For Vertical system,

$$u_v = -\sum_1^9 \sigma_j K_{vj} x_v(t) \quad (27)$$

The conditions for fuzzy controller are mentioned in paper [8]. The controller gain For TRMS-horizontal and TRMS-Vertical are given in paper [8]. Also the Fuzzy observer designed is also provided to make system more accurate [8].

VII. MODEL PREDICTION CONTROLLER

Model prediction control is a numerical method which optimizes control. By performance index, the optimized control inputs are obtained iteratively. This method was used for petrochemical industries only which now expand to wide application such as chemical factories, underwater vehicle, food processing plant, spacecraft station and multiple variables control of huge scale operation problems.In this method, the future input and future output is predicted in this technique.

$$x(k+1) = Ax(k) + Bu(k)$$
$$y(k) = Cx(t) + Du(k) + d(k) \quad (28)$$

Equation for n step prediction is defined as

$$x(k+n) = A^n x(k) + A^{n-1}Bu(k) + A^{n-1}Bu(k+1)$$
$$\ldots\ldots + ABux(k+n-2) + Bu(k+n-1) \quad (29)$$

The output can be defined as for n step,

$$y(k+n) = CA^n x(k) + CA^{n-1}Bu(k) + A^{n-2}Bu(k+1)$$
$$..+ABux(k+n-2) + Bu(k+n-1) + d(K) \quad (30)$$

The simplified equation for input and output are,

$$x(k+1) = P_x x(k) + H_x u(k)$$
$$y(k+1) = Px(k) + Ld(k) + Hu(k) \quad (31)$$

P_x , H_x = prediction parameter
$x(k)$ = measurement
$u(k)$ =decision variable
d(k) = disturbance

VIII. OBSERVER USED FOR TRMS

As system has six states is seen in equation (14), but all states are not measurable since it is highly nonlinear and complex system. The state feedback controller needs all states measurable, then the observer need to design in such a way that it will estimate all states precisely. From past few days the research on observer is taking place. Some rules are considered in this process.

The state space representation for TRMS can be described as,

$$\dot{x} = f(x) + g(x)u$$
$$y = h(x) \quad (32)$$

A. Nonlinear state observer

The nonlinear state observer is a local observer which needs all states of system should be measurable. Considering the all states of TRMS is measurable and designing is done on that basis. The value of $\left[\frac{\partial\phi(\hat{x})}{\partial\hat{x}}\right]^{-1} K$ is given in paper [2]. By putting values, the observer is obtained. It is shown in below,

$$\dot{\hat{x}} = f(\hat{x}) + g(\hat{x})u(+\left[\frac{\partial\phi(\hat{x})}{\partial\hat{x}}\right]^{-1} K(y - h(\hat{x})) \quad (33)$$

K Matrix is chosen so that it satisfy following

$$\|\hat{x}(t) - x(t)\| \le \beta\|\hat{x}(0) - x(0)\|e^{-at}$$

B. Luenberger observer

The Luenberger observer is efficient observer which generates limited noise in all position sensors.

The Luenberger observer can be described by,

$$\widehat{\dot{x}(t)} = f(\hat{x}(t)) + g(\hat{x}(t)u(t) + \left[\frac{\partial\phi_v(\hat{x}(t)}{\partial x}\right]^{-1} L(y - h(\hat{x}(t)) \quad (34)$$

Where, L= matrix of observer

For decoupled i.e. separated horizontal and vertical system, the two observer need to design. The observer equation for TRMS-Horizontal is given as,

$$\widehat{\dot{x}_h} = f_h(\hat{x}_h) + g_h(\hat{x}_h)u_h + \left[\frac{\partial\phi_h(\hat{x}_h)}{\partial\hat{x}_h}\right]^{-1} L_h(x_3 - \hat{x}_4) \quad (35)$$

The observer equation for TRMS-Vertical is

$$\widehat{\dot{x}_v} = f_v(\hat{x}_v) + g_v(\hat{x}_v)u_v + \left[\frac{\partial\phi_v(\hat{x}_v)}{\partial\hat{x}_v}\right]^{-1} L_v(x_1 - \hat{x}_1) \quad (36)$$

The ϕ_h and ϕ_v are given for vertical and horizontal system.

C. Neural observer

Neural observer is advance technique among observers. It does not need all parameters to be known as it needed for local observers. Also it does not need any proper modeling of system. As the TRMS is highly nonlinear, its only two states are measurable, even though neural observer can estimate all states and output can be improved by this.

Neural observer is given by

$$\dot{\hat{x}}(t) = A\hat{x} + \hat{g}(\hat{x}, u) + G(y - C\hat{x})$$

$$\hat{y}(t) = C\hat{x}(t) \tag{37}$$

IX. CONCLUSION

The twin motor MIMO system is similar to helicopter which is used to develop the control algorithms. The TRMS can be controlled by Yaw control and Pitch control similar to helicopter which is 2 Degree of freedom (DOF). The Yaw controls the horizontal movement i.e. left and right motion of tail rotor of TRMS. The Pitch controls the vertical movement i.e. upward and downward motion of main rotor of TRMS.In this paper, different controlling methods of TRMS are explained with their mathematical proofs. PID control is very oldest and efficient method but because of their some drawbacks, it combined with some other techniques which apply on the TRMS and results are obtained. Also sliding mode control is one of the finest methods of controlling. Only the chattering problem of SMC is eliminated by second order sliding mode control (SOSMC). T- S fuzzy mode method is based on Linear Matrix Inequality (LMI) which has some rules, assumption and membership function. Model prediction control technique can predict future input and future output that helps the TRMS to work more efficient way. The observers can make the system more efficient way as it calculates error between estimated system and actual system. And that error is again given to system and that makes accuracy of TRMS improves.

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