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Twin Rotor MIMO System.

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RESUMEN

Este trabajo comprende el análisis matemático, construcción y control de un equipo de laboratorio que cumpla con todas las características de un Sistema MIMO de Rotores Gemelos (TRMS, por sus siglas en inglés). Se analiza el modelo dinámico de un TRMS con el fin de identificar las características más relevantes de un TRMS. Algunos de los componentes son diseñados mediante el uso de software CAD, y fabricados en un torno. El control del TRMS se efectúa mediante el uso de hardware embebido.

Palabras clave: TRMS, Sistema MIMO, Rotores Gemelos, Identificación de modelo, construcción de TRMS, control de TRMS.

ABSTRACT

This paper reports on the mathematical analysis, construction and control of a laboratory system that fulfills all the characteristics of a Twin Rotor MIMO System (TRMS). The dynamic model of a TRMS is analyzed in order to recognize the most relevant characteristics of a TRMS. Most of the components are designed using CAD software and manufactured in a lathe machine. Control of the TRMS is performed using embedded hardware.

Key words: TRMS , MIMO System, Twin Rotor, Model Identification, TRMS construction, TRMS control.

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Twin Rotor MIMO System

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***Abstract*—This paper reports on the mathematical analysis, construction and control of a laboratory system that fulfills all the characteristics of a Twin Rotor MIMO System (TRMS). The dynamic model of a TRMS is analyzed in order to recognize the most relevant characteristics of a TRMS. Most of the components are designed using CAD software, and manufactured in a lathe machine. Control of the TRMS is performed using embedded hardware.**

I. Introduction

A Twin Rotor MIMO System (TRMS) is a laboratory equipment that simulates a helicopter. It consists of a beam rotating around a fixed point called pivot. The beam can rotate in the horizontal plane, and the vertical plane. A TRMS has two engines with a propeller placed at each end of the beam. One propeller is oriented vertically, and the other is oriented horizontally. An important characteristic of this system is the cross-coupling effect generated by the rotation of the two propellers. The multiple inputs and outputs of a TRMS, and the cross-coupling effect are the key characteristics that make the design of controllers for this device a real challenge.

During previous years, several methods have been used to find a dynamic model of the TRMS [1]; but, due to its high non-linearity and cross-coupling properties, it has been challenging to get a model that explains accurately the behavior of this system. Previous research presents a mix of theoretical and experimental methods to find a reliable dynamic model, and design a controller.

To simplify the model, many authors have linearized the model, and in some cases even neglect all non-linearities. However, the effect of ignoring non-linearities results in a limited dynamic model, that requires adjustment to every operating point in order to design effective controllers [2].

This project's objective is the construction of a plant that fulfills all the characteristics of a Twin Rotor MIMO System derived from a mathematical model such that most non-linearities and couplings can be amplified with the purpose of proposing a challenging control exercise.

This paper is organized as follows: Section 2 introduces the dynamic model of a TRMS, and identifies the most relevant components in the mechanics of the system. Section 3 shows the design of the mechanical components of the TRMS. The electronic issues are presented in Section 4. It includes sensors, conditioning circuits, and software used to control the plant. In section 5, the results of a simple control exercise in this plant are presented. Three different examples illustrate how the characteristics of the TRMS make of this system a challenging exercise. Finally, at the end of this paper, the conclusions are drawn.

II. Dynamic Model

It is important to recognize the different parts of a Twin Rotor MIMO System in order to understand the origin of the dynamic model. For simplicity, this device can be divided into four different sections as shown in Figure (1).

The first component is the base of the TRMS. The pivot is located at the top of this structure (see Figure (1)). The second component will be called "the main section" This includes the propeller that generates vertical thrust (main rotor), the shield covering of this propeller, and the portion of the beam located between the pivot and the main rotor. Third, the "tail section" includes the propeller that generates horizontal thrust (tail rotor), it's shield covering, and the portion of the beam located between the pivot and the tail rotor. Finally, the "counterweight section" includes the beam perpendicular to the main beam, and the mass located at its end.

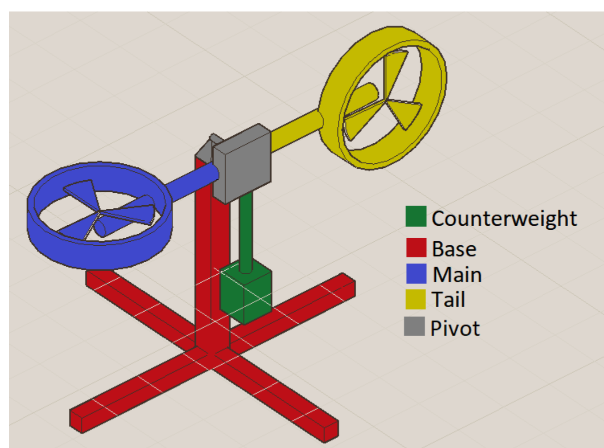

Fig. 1: TRMS structure

The first step in this work is finding a dynamic model that shows the effect of each part in the mechanic behaviour of the system, including the cross-coupling. There are many different methods used to find a dynamic model for a TRMS reported in literature, but the one whose parameters best fit to our requirements is the Newtonian Method. This method, requires the application of basic physics concepts, specifically sum of forces acting on an object, torques, and circular motion.

In [3], is presented a model using the Newtonian Method. This method uses parameters which can be easily measured in a TRMS, like lengths and masses of the different components. It starts by analyzing the forces created by the motors that move the propellers, and then, the forces acting in the horizontal and vertical planes. These parameters can be identified in Figure (2)

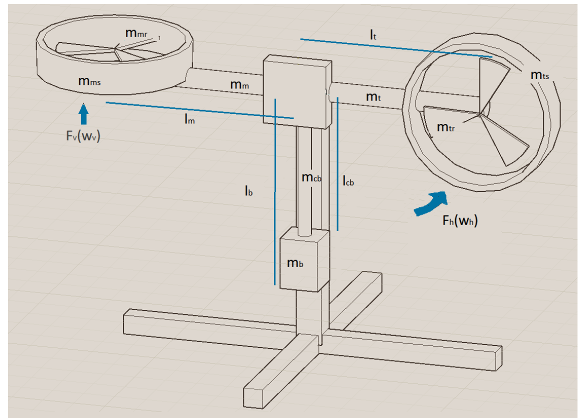

Fig. 2: Variables identification in vertical and horizontal plane

A. DC Motors

The motor's performance is described in this section. Equation (1) shows how an input voltage generates an EMF in the motor. Equation (2) describes how that EMF generates motion in the rotor. And Equation (3) shows how the moment of inertia of each motor influence its motion. These three equations together are form a state equations system. Most of the parameters used in these equations are exclusive of each motor. This cannot be changed at will, and they are given by the motor's manufacturer. The parameters are presented in Table (I).

TABLE I: Motor Parameter Definitions

Parameter	Description
$V_{h/v}$	Voltage terminal in tail/main motor.
$E_{ah/v}$	EMF of tail/main motor.
$R_{ah/v}$	Armature resistance of tail/main motor.
$i_{ah/v}$	Armature current of tail/main motor.
$L_{ah/v}$	Armature inductance of tail/main motor.
$k_{ah/v}\varphi_{h/v}$	Torque constant
$\omega_{h/v}$	Angular speed of tail/main rotor.
$M_{eh/v}$	Electro-magnetic torque of tail/main motor.
$M_{Lh/v}$	Load torque of tail/main motor.
$J_{tr/mr}$	Moment of inertia of tail/main motor.
$B_{tr/mr}$	Viscous friction coefficient of tail/main motor.

$$V_{h/v} = E_{ah/v} + R_{ah/v} i_{ah/v} + L_{ah/v}\frac{di_{ah/v}}{dt} \quad (1)$$
$$E_{ah/v} = k_{ah/v}\varphi_{h/v}\omega_{h/v} \quad (2)$$
$$M_{eh/v} = M_{Lh/v} + J_{tr/mr}\frac{d\omega_{h/v}}{dt} + B_{tr/mr}\omega_{h/v} \quad (3)$$

B. Vertical Plane

The Vertical plane movement model is shown in equation (9). It takes in consideration the torque made by the propulsive force of the main rotor (Equations (4) and (5)), torque produced by friction force (this includes friction in the bearing of the pivot and air resistance), and torque produced by the weight of all the elements of the plant. For simplicity at the moment of reading Equation (9), Equations (6), (7) and (8)are introduced. Every variable used in this model can be identified in Figure (2).

$$F_v(\omega_v) = k_{fvp}|\omega_v|\omega_v \text{ ; for } \omega_v \geq 0, \quad (4)$$
$$F_v(\omega_v) = k_{fvn}|\omega_v|\omega_v \text{ ; for } \omega_v < 0, \quad (5)$$
$$A = \left(\frac{m_t}{2} + m_{tr} + m_{ts}\right) l_t \quad (6)$$
$$B = \left(\frac{m_m}{2} + m_{mr} + m_{ms}\right) l_m \quad (7)$$
$$C = \frac{m_b}{2} l_b + m_{cb} l_{cb} \quad (8)$$
$$\frac{d\Omega_v}{dt} = \frac{l_m F_v(\omega_v) - M_{fricv}}{J_v} + \frac{g[(A-B)cos(\alpha_v) - Csin(\alpha_v)]}{J_v} \quad (9)$$
$$\frac{d\alpha_v}{dt} = \Omega_v \quad (10)$$

C. Horizontal Plane

Horizontal plane movement is presented in Equation (16). It takes in consideration the torque produced by the propulsive force of the tail rotor (Equations (11) and (12)), torque produced by friction forces, and torque of resultant tension of cables elongation due to the rotation of the beam. For simplicity at the moment of reading Equation (16), the moments of inertia of main and tail sections, counterweight section, and shields are presented in Equations (13), (14) and (15) respectively., Variables can be identified in Figure (2).

$$F_h(\omega_h) = k_{fhp}|\omega_h|\omega_h \text{ ; for } \omega_h \geq 0, \quad (11)$$

$$F_h(\omega_h) = k_{fhn}|\omega_h|\omega_h \text{ ; for } \omega_h < 0, \quad (12)$$

$$D = (\frac{m_m}{3} + m_{mr} + m_{ms})l_m^2 + (\frac{m_t}{3} + m_{tr} + m_{ts})l_t^2 \quad (13)$$

$$E = \frac{m_b}{3}l_b^2 + m_{cb}l_{cb}^2 \quad (14)$$

$$F = m_{ms}r_{ms}^2 + \frac{m_{ts}}{2}r_{ts}^2 \quad (15)$$

$$\frac{d\Omega_h}{dt} = \frac{l_t F_h(\omega_h)cos(\alpha_v)}{Dcos^2(\alpha_v) + Esin^2(\alpha_v) + F} + \frac{-M_{frich} - M_{cable}(\alpha_h)}{Dcos^2(\alpha_v) + Esin^2(\alpha_v) + F} \quad (16)$$

$$\frac{d\alpha_h}{dt} = \Omega_h \quad (17)$$

D. Cross-coupling

This model considers two different torques affecting the vertical angle (α_v) that are caused by the cross-coupling effect. Centrifugal torque is caused by the rotation of the beam in the horizontal plane [1], and it is expressed in Equation (19). For simplicity at the moment of reading this equation, Equation (18) is introduced.

$$H = Al_t + BL_m - \frac{m_b}{2}l_b^2 - m_{cb}l_{cb}^2 \quad (18)$$

$$M_{cent} = -\Omega_v^2 Hsin(\alpha_v)cos(\alpha_v) \quad (19)$$

Gyroscopic torque is caused by the rotation of the main rotor. The propeller is considered a rotating disc in order to simplify the physical model (Equation (20)), where k_g is a constant.

$$M_{gyros} = k_g F_v(\omega_v)\Omega_h cos(\alpha_v) \quad (20)$$

Taking in consideration the cross-coupling torques, the complete vertical plane plane dynamics can be described in Equation (21).

$$\frac{d\Omega_v}{dt} = \frac{l_m F_v(\omega_v) - M_{fricv} + g[(A-B)cos(\alpha_v)}{Jv} - \frac{Csin(\alpha_v)] + M_{gyros} + M_{cent}}{J_v} \quad (21)$$

The dynamic model shows that the base is the only component of the TRMS that does not affect directly the mechanics of the system. The entire system's behavior depends on the masses and lengths of the main, tail, and counterweight sections, so it is important to consider every single element to build a functional TRMS.

III. Mechanical construction of the TRMS

The work presented in [4] will be used as a starting point in the design of the different components of the TRMS. This work presents the different components and the procedure to build a TRMS. Some elements were modified in order to obtain a more efficient plant.

A. Base of the TRMS

The TRMS base presented in [4] consists of a steel hollow structure, strong enough to hold all the weight of the plant, and heavy enough to avoid vibration caused by the operation of the rotors. The presence of this structure is not evident in the dynamic model, but it is extremely important that the TRMS has a completely static base, so any external motion will not affect the dynamics of the system. The blueprint is shown in Figure (3).

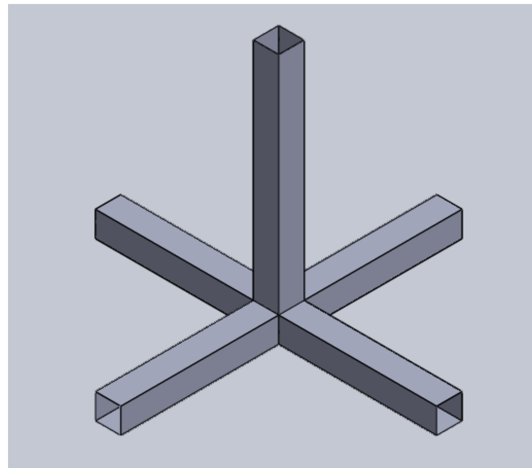

Fig. 3: TRMS Base.

B. Main and Tail and counterweight Sections

The main section is supported by carbon fiber pipes. This material is light and strong. One end of the beam is connected with the pivot, and the other end holds a rotor. The propelling system is an Air Gear 350, which includes propellers, motors, and an Electronic Speed Controller (ESC) for each motor. All the required wiring is fixed along the beam in order to avoid any extra tension caused by the cables. Propellers can take damage if they hit something or someone when the motors are spinning, so it was necessary to build a shield for protection. The shields were designed in Auto CAD (Figure (4)), and manufactured with PLA , in a 3D printer.

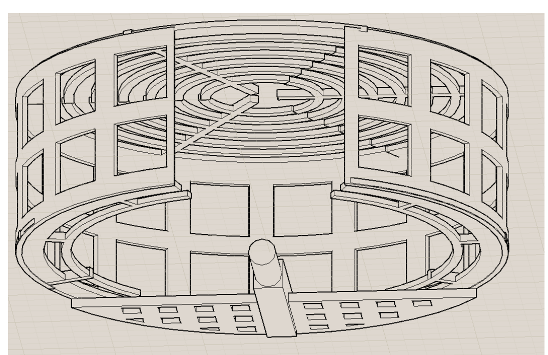

Fig. 4: Shield for propeller.

The tail section is meant to be symmetric to the main section, taking the pivot as a reference. It is symmetric because the beam, motor, propeller, shield and wiring are exactly the same. The only difference is the orientation of the propeller. As the main propeller gives a vertical impulse, the tail propeller gives horizontal impulse.

The counterweight section is made of a stainless steel pipe, perpendicularly oriented to the main and tail beam. In order to give more weight to this section, the pipe was filled with steel, and an iron mass of $250mg$ was added to the end of the pipe.

C. Pivot

The pivot connects strongly every section of the TRMS, and at the same time, allows the desired range of movement. An appropriate design for the pivot must make sure that the precision potentiometers used as position sensors make a reliable measurement, and with the use of bearings, reduce the friction. Four pieces were designed in Auto CAD, and manufactured in aluminum.

The first part is presented in Figure (5). The function of this part is to join the base with the mobile part of the plant, hold a sensor, and lead the rotation in the horizontal plane.

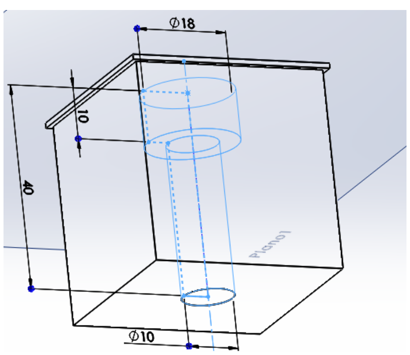

Fig. 5: Pivot part number 1

The second part is shown in Figure (6). This part is connected to part number 1 through a bearing. This part acts as a support that holds the upper part of the TRMS, and the sensor that measures the vertical angle.

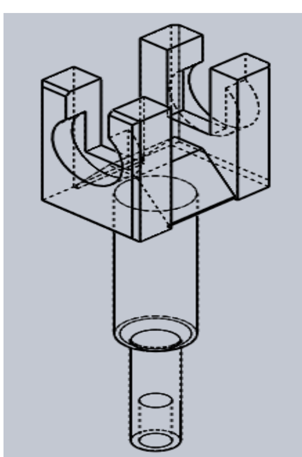

Fig. 6: Pivot part number 2

The third part is shown in Figure (7). This component is connected to part number 2 through a bearing, and rotates around its own axis, activating the sensor that measures the vertical angle.

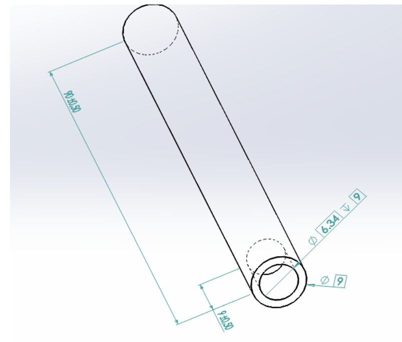

Fig. 7: Pivot part number 3

The fourth part is presented in Figure (8). This part connects the main beam, tail beam, and counterweight beam. It is connected with part number 3.

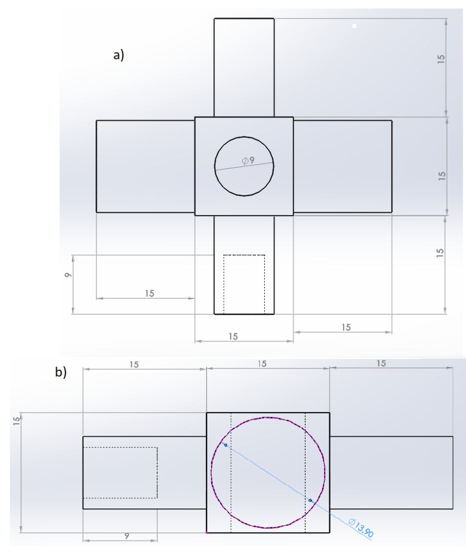

Fig. 8: Pivot piece number 4. a) upper view b) front view

These four parts together form the mobile section of the TRMS. The use of bearings and precision potentiometers ensure a negligible friction force.

IV. Electronics.

A. Sensors

The TRMS requires the measurement of two values: the angle in the vertical plane and the angle in the horizontal plane. These are measured with two precision potentiometers. Bornus 3541 is a $10K\Omega$ potentiometer [5]. It has an effective electrical angle of 3600 degrees. This is used to measure the horizontal plane angle. Vishay Spectrol Model 132 is a $10K\Omega$ potentiometer that has an effective electrical angle of

352 degrees [6]. This is used to measure the vertical plane. Both potentiometers are polarized with a $5V$ power supply, and the measurement is read by a NI MyRIO-1900. It is important to design a conditioning circuit in order to clean the measured signals (output signals), and limit any surge which could compromise the NI MyRIO card. The circuit has a potentiometer (R1) used as sensor, an isolation amplifier which receives the measurement of the sensor, a RC low-pass filter, and a $5.1V$ zener diode. The circuit is presented in Figure (9)

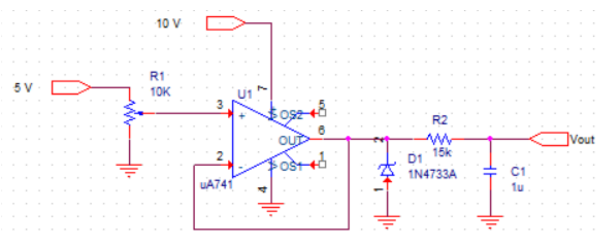

Fig. 9: Conditioning circuit

The same circuit is used to isolate the signal from Bornus 3541 and Vishay Spectrol Model 132.

B. Rotors

Every propeller is impulsed by a motor, that is activated by using an Electronic Speed Controller. This motor's performance goes according to Figure (10).

Item No.	Voltage, V	Prop	Throttle	Current, A	Power, W	Thrust, g	RPM	Efficiency, g/W
AIR 2213 KV920	11.1	T9545	50%	2	22.2	240	4400	10.81
			65%	3.8	42.18	386	5900	9.15
			75%	5.5	61.05	490	6900	8.03
			85%	7.2	79.92	594	7800	7.43
			100%	9.8	108.78	722	8300	6.64
	12		50%	2.3	27.6	278	4800	10.07
			65%	4.4	52.8	445	6300	8.43
			75%	6.2	74.4	568	2200	7.63
			85%	8.1	97.2	679	8100	6.99
			100%	10.9	130.8	813	8900	6.22
	14.8		50%	3.3	48.84	403	5700	8.25
			65%	6.2	91.76	636	7600	6.93
			75%	8.4	124.32	786	8600	6.32
			85%	10.7	158.36	907	9500	5.73
			100%	14.3	211.64	1084	10200	5.12

Fig. 10: Technic details of T-Motor AIR 2213 KV920

The ESC receives $12V$ from the power source, and a control signal in order to deliver the required current to the motor. The control signal is a PWM with frequency of $50Hz$, and a duty cycle that varies between the 5% and 10%. This signal will be generated by the device NI MyRIO-1900.[7]

C. Conditioning Circuit

A power source is used to feed the entire system. It supplies $12V$, enough to feed the plant, but it creates noise that can affect input and output data signals. In order to solve this problem, a conditioning circuit was designed, so power signals and control signals are completely isolated.

The isolated DC/DC converter IM2405S was used to isolate power and control signals [8]. It receives the power signal ($12V$) and delivers the supply voltages for sensors ($\pm 5V$).

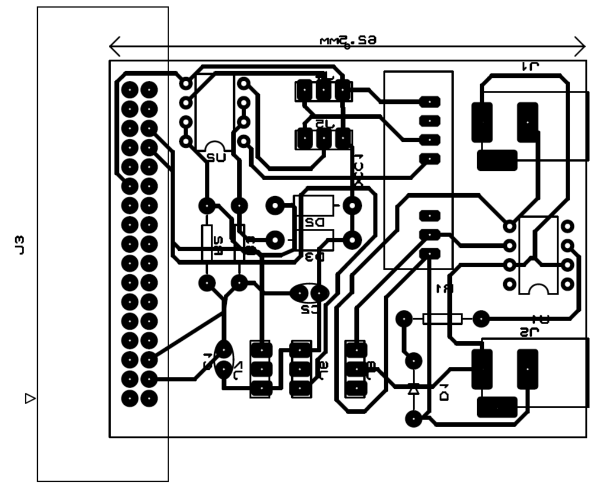

Fig. 11: PCB Design for TRMS Conditioning Circuit.

All these circuits are combined in a single PCB. This PCB is directly connected to motors, sensors, power supply, and the MyRIO-1900. For simplicity with the connection of every electronic element, the PCB was manufactured with a ”1900 MyRIO Protoboard kit MXP”.

D. Software

The TRMS is controlled by a graphic interface made in LabVIEW. The MyRIO Toolkit is necessary in order to enable the analog I/O, and the PWM pins. Pins 3 and 5 send a PWM with a frequency of $50Hz$ and a duty cycle that varies between 5% and 10%, in order to activate the motors. And pins 27 and 29 read the measurements of the sensors. The interface of the program is shown in Figure (12). It displays waveform charts, showing the input and output signals of the system.

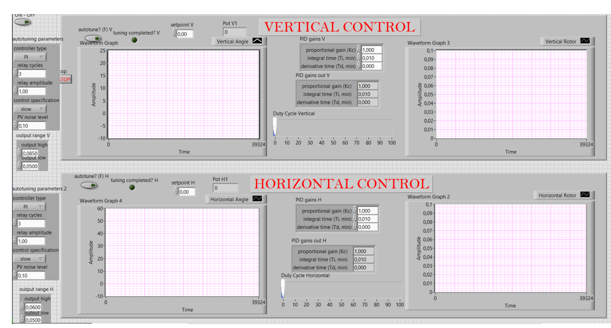

Fig. 12: LabVIEW program's interface

The program includes a PID controller for each motor, implemented using LabVIEW's tool, PID Autotuning. This controllers do not take in consideration the cross-coupling effect of the TRMS, so it is considered that vertical angle is affected only by main rotor, and horizontal angle is only affected by tail rotor.

V. Results

Three tests were made, applying different setpoints for vertical and horizontal angles.

The first test was made applying a setpoint of 30^o for the vertical and horizontal angles. Figures (13) and (14) show the result of this test. Vertical angle does not reach the 30^o of inclination. It gets 24^o in its highest peak, and remain oscillating during the test. However, horizontal angle lightly oscillates around 32^o, getting a more stable behavior.

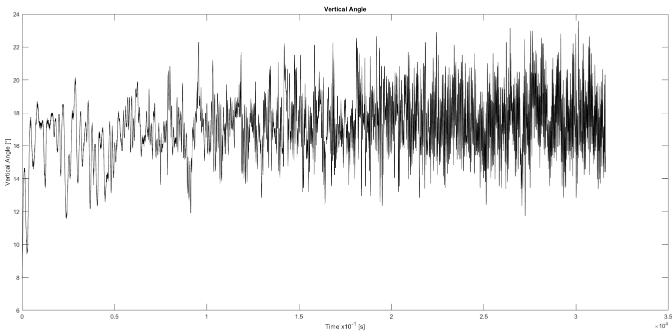

Fig. 13: Vertical Angle with Setpoint 30^o

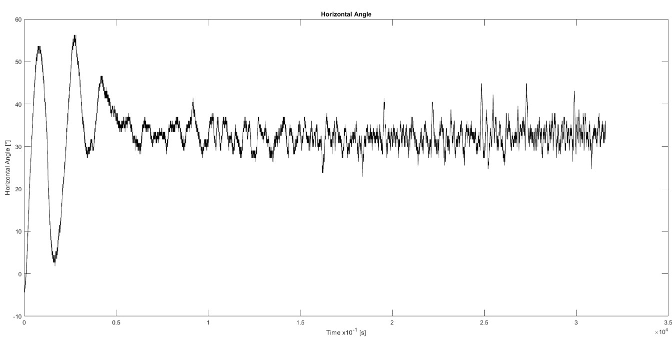

Fig. 14: Horizontal Angle with Setpoint 30^o

The second test is shown in Figures (15) and (16). A setpoint of 20^o was applied for the vertical angle, and 15^o for the horizontal angle. The vertical angle keeps oscillating around 17^o during all the test. Horizontal angle remains oscillating around 23^o, even when the setpoint is much lower than that. In this case, vertical and horizontal angles are far away of the desired result.

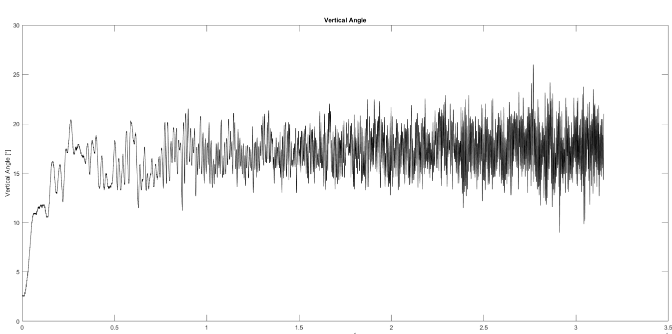

Fig. 15: Vertical Angle with Setpoint 20^o

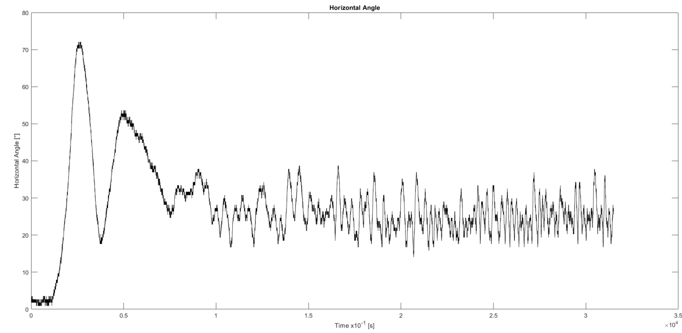

Fig. 16: Horizontal Angle with Setpoint 15^o

The third test, shown in Figures (17) and (18), was made applying a setpoint of 40^o for the vertical angle, and 45^o for the horizontal angle. In this case, the vertical angle gets an stable behavior around 29^o. And the horizontal angle also gets stable around 45^o. In this case, the horizontal PID works perfectly, but the vertical, even if it gets stable, the angle is away of the setpoint.

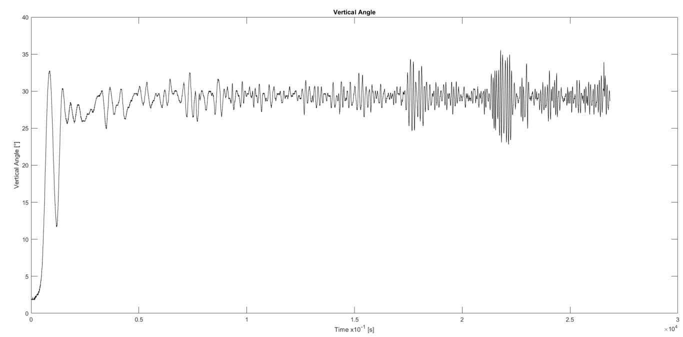

Fig. 17: Vertical Angle with Setpoint 40^o

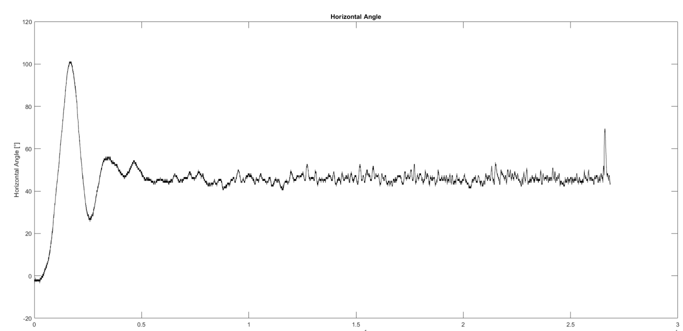

Fig. 18: Horizontal Angle with Setpoint 45^o

VI. Conclusion

This paper presents the modelling, construction and control of a Twin Rotor MIMO System. All the parts can be easily manufactured taking the designs presented in this paper, and all the electronic parts can be found in online stores. This means that it is feasible to build a functional handmade TRMS.

The plant fulfills all the requirements to be called a TRMS. It has two rotors, a free motion on the vertical and horizontal planes, and a marked cross-coupling effect. However, the plant presents a limitation. Due to the weight of the plant, the vertical angle can increase up to 30^o.

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[8] X. Power, *2 Watts - IM Series*, XP Power.