Edinburgh Napier
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Mechatronic Systems

MEC10105

Coursework 2: 2-DOF Helicopter System Design Report.

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Abstract:

This report will present an account of the work undertaken to answer the design requirement of Flight Academic Training Ltd for a 2-DOF Helicopter prototype.
The W-Model design methodology was chosen to help manage the solution development process.

Tasks were split between Conceptual Design, Embodiment Design and Controller Design.

Several documents (appended to this report) were created to solve the engineering problem:

- Product Design Specification.
- Mechanical Drawings.
- Electrical Schematic.
- Mathematical Model.
- Virtual Model.

Table of Content

This report will present an account of the work undertaken to answer the design requirement of Flight Academic Training Ltd. The purpose of the project is to follow a defined mechatronics design methodology to deliver a working solution as fast as possible as a multi-disciplinary engineering team. The report is broken down in five parts.

The first part (Conceptual Design) gives an overview of the needs, functions and information gained from the design brief as well as an understanding of the interaction between the different functions and parts making the solution.

The second section (Embodiment Design) gives an account of the software tools used, a description of the selected components (and related software) and an overview of the technical drawings realised.

Then, an explanation of the selected control method and mathematical model is given followed by a simulation of the application.

Finally, conclusions will be drawn on the work realised, more general aspects of the project and design methodology used.

I. Conceptual Design.

This section will describe the preliminary steps taken to gain an understanding of the problem statement and understanding the needs of the client up until definition of the main functions, system and subsystems required to develop a solution.

Problem Statement - Customer Needs

Flight Academic Training Ltd requires a 2 DOF (Degree Of Freedom) helicopter to model to use for demonstration within their helicopter pilot training course and over public engagement exercises. The model requires to follow a defined pitch and yaw coordinate sequence to demonstrate the position adjustments of a helicopter system. Figure 1.1 shows a simple demonstration of the basic mechanics of the application.

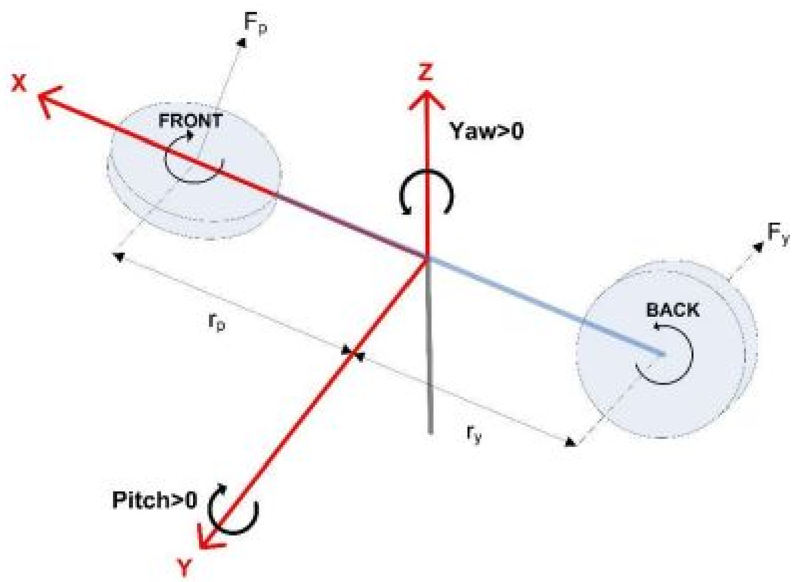

Figure 1.1 2-DOF Helicopter System Mechanics.

Product Design Specifications

The product design specifications give an overview of the requirements, constraints and functions of the technical solution. They are derived from the client's design brief and subsequent interviews.
The product design specifications document has been organised around 5 main axis: Mechanical, Electrical and Electronics, Operation and Performance, Ergonomics and Interface, Manufacturing Capabilities.
As the problem, requirements and functions are better understood and become more defined, it is possible to update the various sections with the new information. Between each installment of the PDS, the upgrades would have to be validated by the client (especially relevant for additional features).

The document has been updated several times since the first installment. The latest updates are:

- Mechanical: The horizontal beam is now replaced with two rods fitted onto a yoke system attached to the vertical shaft. The fans are now mounted onto frames which are screwed onto the two rods. The vertical shaft is fitted in bearings to secure it to the rest of the system and main base.
- Electrical: The two sensors positions have been defined. The microcontroller system has been upgraded to an Arduino Mega.
- Operation and Performance: The Yaw angle has been restricted to 120 degrees. A factory acceptance test has been added to the previous FTS.
- Ergonomics and Interface: Specific consumer regulations guidelines have been added. Additional safety grids are added to the fans.

An updated copy of those specifications can be found in appendix A of this report.

Function Chart

From the product design specification it is possible to identify the primary and subfunctions to be performed by system. Function identified In the 2-DOF Helicopter system:

- Primary Function: Helicopter control pitch and yaw.
- Subfunctions: System On, Mode Selection, Automatic/Manual Sequence and Emergency Stop Sequence.

Those functions can be organised in a function chart as described in Figure 1.2 (also available in Appendix B). Each of the blocks receives inputs and creates outputs which can be: Energy, Material or Signals.

The primary function requires all of the subfunctions to be able and fulfil its purpose. The subfunctions can be arranged in a logical order to demonstrate the interdepencies and interaction of functions and components.

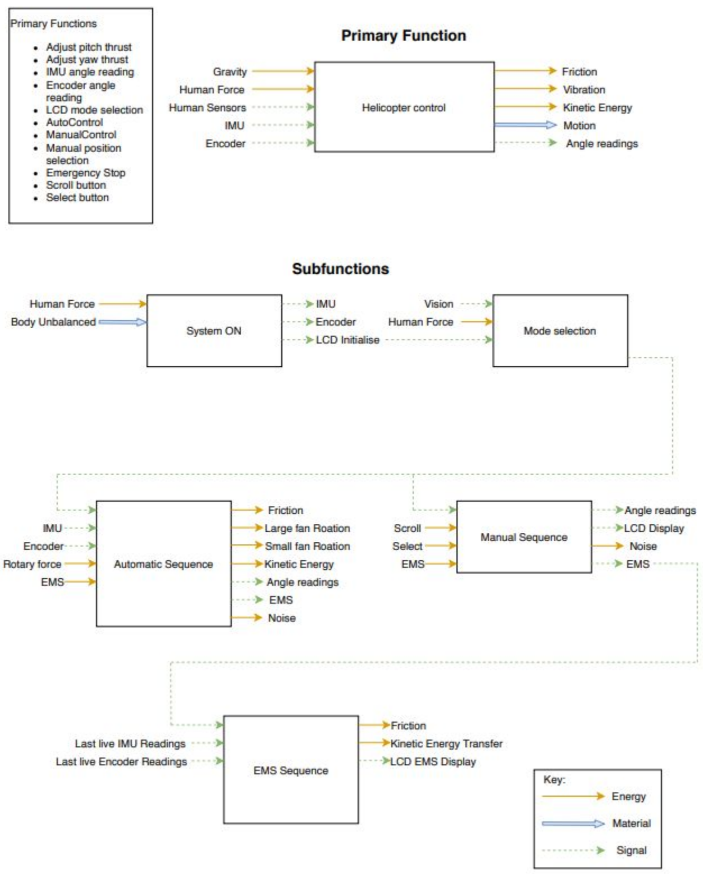

Figure 1.2 Helicopter Control Function Chart (available in Appendix B).

II. Embodiment Design.

This part of the report describes the activities undertaken to bring the applications from functions and concept towards the physical and final prototype. At this point, mechanical, electrical, control and software development are happening concurrently.

Description of software tools

This section gives a short overview of the software tools used for the various development activities:

Autodesk Inventor - Inventor is a computer-aided design (CAD) software package. It is used to design and analyse mechanical parts, assemblies and processes. It can output technical drawings, 3D representations and animations.
Eplan - is an electrical schematic design software. It allows to create electrical following appropriate standards and helps in the creation of technical documentations.
MATLAB Simulink - Simulink is a software package part of MATLAB allowing to model, tune and simulate processes based on mathematical formulas.
Arduino IDE - is a development environment for Arduino and Arduino compatible development boards and systems. Those can be programmed using the Arduino language derived from C/C++. The compiler will also accept C/C++ languages.

Electrical Components and Software Application

This section will give an overview of the selected components with a short explanation of their purpose and working principles within the application.

Power Supply Unit (PSU) - This component supplies 12V of power to the system. The power line uses splitters to distribute the power around.

Arduino Mega Controller - As mentioned previously the Arduino was upgraded to an Arduino Mega. This is due to requiring 18 digital I/Os in the application. The controller manages the signal acquisition and data processing from the sensors to be used in the PID controllers software. It then conditions the output signals to be sent to the actuators. The Arduino also manages the user interface aspects with the push buttons, EMS and LCD display.

Motor Control Shield - The component receives the PWM digital signals from the Arduino and conditions the output power according to control the speed of the fans. This shield allows control of up to 4 fans in both directions (with compatible fans).

Rotary Encoder - This is an incremental two outputs signal encoder. Each pin returns a high or low signal allowing to determine which way the encoder is going (increment/decrement) according to the sequence of previous and current state. The number of incrementations (one way or another) is used to calculate the angle from a reference point.

Inertial Measurement Unit - Using the accelerometer and the readings from axis x and z it is possible to calculate the current angle using the atan function.

Push Buttons - Those are used to interface with the system. One allows the users to scroll in the menus and another select/ validate.

Emergency Stop - This can be depressed to trigger the emergency stop: shutting down and resetting the systems.

LCD Display - Is used to display the menus and allow the users to select the operating mode, the current angle reading and the current pitch and yaw coordinates.

Large Fan - This fan set is at the front of the system and will control the pitch of the system. These fans can directly receive PWM control signals from the Arduino.

Small Fan - This fan set is connected to the motor control because they do not have a PWM signal control therefore the voltage variation from the motor control shield will serve as a speed control.

15 core coil Cable - The cable allows for an easy management of power and signal routing. Moreover, its flexibility allows the system to stay tidy but for the cable to stretch when in operation.

Technical Drawings

This section gives an account of the different technical drawings created (mechanical and electrical) to allow the manufacturing and assembly of the prototype.

Electrical Schematic (Appendix C) - The document was realised using Eplan. It demonstrates how the electrical components, previously presented, interface with each other. This allows to easily identify signal and power cable during the assembly and troubleshooting.

Mechanical drawings created using Autodesk Inventor. Those are used by the machine shop to manufacture and assemble the various parts:

Full Assembly (Appendix D) - This gives an overview of the fully assembled prototype. It allows the identification of the different subassemblies of the design.

Plates (Appendix E) - The document shows the sizing of the different plates (base, User Interface and shaft elevation) with the placement of the fixture points for the spacers.

Block Assembly (Appendix F) - The block assembly serves as a mount for the bearings allowing for the vertical shaft to rotate. The document provides the sizes as well as the mounting points location to the shaft elevation plate and for the encoder.

Fan Mount (Appendix G) - Provides the details for the two fan sets mounting frames with the mount block to allow fitting onto the rods.

Yoke Drawing (Appendix H) - Shows the three elements required for the yoke mechanism. The housing holds the body thanks to the pin. The rods screw into the body to mount the fan systems to the vertical shaft.

Rods (Appendix I) - Shows the sizing of the three rods: front and back fan systems and yoke to vertical fan fixture.

Safety Considerations

This section describes some of the steps taken to ensure the safety of the final prototype.

Two testing procedure documents have been created. First the Factory Acceptance (Appendix J) Test which offers a framework to test relevant points of the manufactured product. Secondly, the Functional Test Specification (Appendix K) which tests for functionalities linked to the normal usage of the prototype.

Finally, Figure 2.1 shows an example of the safety reminder information available on the user interface panel.

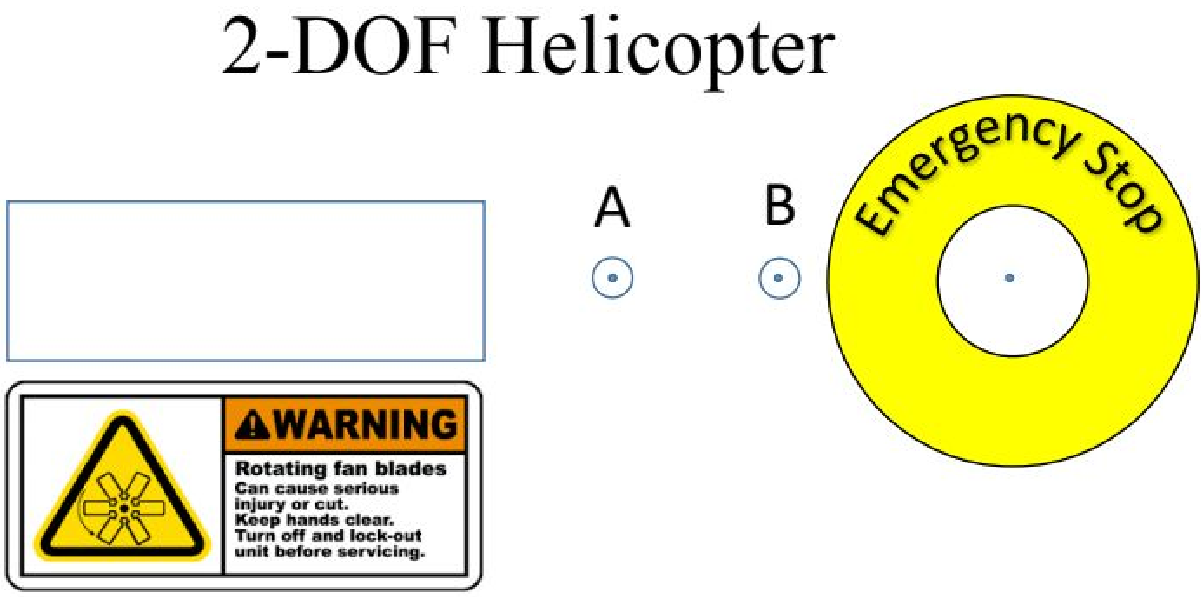

Figure 2.1 UI Panel.

III. Control System Design.

Control Method Justification

In this 2-DOF Helicopter application, the controller needs to control the position of the pitch and yaw simultaneously. The pitch angle variation will be measured by the IMU and the yaw angle by the rotary encoder. Moreover the controller has to output two different signals: one for the front rotors and one for the back rotors. Seborg (1989) qualifies these systems as multivariable control in which all errors contribute to the overall control strategy. The system will therefore be controlled by a Multi Input Multi Output controller composed of two PID controllers with decouplers to counter attack the effect of each axis on one another.

Calculations

This section gives an explanation of the mathematical derivations realised to obtain the mathematical model of the MIMO system control for the Helicopter system. The virtual models are available in Appendices L and M.

Variables - Some of the values are constant based on information available from similar components:

θ = Pitch angle.

φ = Yaw angle.

V_p = Voltage at pitch rotor.

V_y = Voltage at yaw rotor.

D_p = Damping about pitch (0.00711 Vs/rad).

D_y = Damping about yaw (0.0220 Vs/rad).

K_{sp}= Stiffness about pitch (0.0375 Nm/rad).

K_{pp} = Pitch torque thrust about pitch (0.0011 Nm/V).

K_{yy} = Yaw torque thrust about yaw (0.0022 Nm/V).

K_{yp} = Yaw torque thrust about pitch (-0.0027 Nm/V).

K_{py} = Pitch torque thrust about Yaw (0.0021 Nm/V).

When the body is parallel to the ground:

$J_p\,\theta'' + D_p\,\theta' + K_{sp}\,\theta = T_{pitch}$

$J_y\,\varphi'' + D_y\,\varphi' = T_{yaw}$

Where torques are:

$T_{pitch} = K_{pp}\,V_p + K_{py}\,V_y$

$T_{yaw} = K_{yp}V_p + K_{yy}\,V_y$

Moments of inertia are:

$J_p = J_{body} + 2J_{prop}$

$J_y = J_{body} + 2J_{prop} + J_{yoke}$

Inertia of a rotor as a single mass point:

$J_{prop} = m_{prop}\,r_{prop}^{2}$

Inertia of the body as a cylinder rotating about the vertical axis :

$J_{body} = (m_{body}\,L_{prop}^{2})/12$

$J_{yoke} = (m_{yoke}\,r_{yoke}^{2})/2$

Laplace transforms of system of equations $T_{pitch\ and}\ T_{yaw}$:

$J_p\,\theta(s)s^2 + D_p\,\theta(s)s + K_{sp}\,\theta(s) = K_{pp}\,V_p(s) + K_{py}\,V_y(s)$

$J_y\,\varphi(s)s^2 + D_y\,\varphi(s)s = K_{yp}\,V_p(s) + K_{yy}\,V_y(s)$

Laplace transform equations for transfer functions of system motions relative to each inputs:

$$\frac{\theta(s)}{V_p(s)} = \frac{K_{pp}}{J_{ps}{}^2 + D_{ps} + K_{sp}}$$

$$\frac{\varphi(s)}{V_p(s)} = \frac{K_{yp}}{J_y s^2 + D_{ys}}$$

$$\frac{\theta(s)}{V_y(s)} = \frac{K_{py}}{J_p s^2 + D_{ps} + K_{sp}}$$

$$\frac{\varphi(s)}{V_y(s)} = \frac{K_{yy}}{J_y s^2 + D_y s}$$

MIMO Decoupler Calculations:

For first to second loop decoupler:

$$-\frac{\dfrac{K_{yp}}{J_y s^2 + D_y s}}{\dfrac{K_{yy}}{J_y s^2 + D_y s}} = -\frac{K_{yp}}{K_{yy}}$$

For the second to first loop decoupler:

$$-\frac{\dfrac{K_{py}}{J_p s^2 + D_p s + K_{sp}}}{\dfrac{K_{pp}}{J_p s^2 + D_p s + K_{sp}}} = -\frac{K_{py}}{K_{pp}}$$

Results of J_p and J_y Inertia and Decoupler Calculations:

The body mass was estimated from the mass of a 265mm rod.

Moment of Inertia Jp & Jy - Decouplers for MIMO

m Large Prop	0.2635
m Small Prop	0.1085
r Large Prop	0.1
r Small Prop	0.25
JpropLarge	0.002635
JpropSmall	0.006781

mYoke(kg)	0.134
rYoke(m)	0.02
Jyoke	0.000026

mBody(kg)	0.050943
Lbody(m)	0.3
Jbody	0.001273

Jp (kg/m2)	0.02010608491
Jy (kg/m2)	0.02013288491

Second to first loop decoupler	
Kpy (Nm/V)	0.0021
Kpp (Nm/V)	0.0011
Decoupler	-1.909090909

Body mass estimation from rod		
	Rod	Body
mass (kg)	0.045	0.0509433
Length (m)	0.265	0.3

First to second loop decoupler	
Kyp (Nm/V)	-0.0027
Kyy (Nm/V)	0.0022
Decoupler	1.227272727

IV. Simulation & Evaluation.

This section will give short explanations about the controller tuning and the results of the various simulations of the system in operation using the two virtual models (Appendices L and M).

PID Gain Values

The PID gain values were obtained using the PID Tuner programme within simulink.

Tuning process:

1. The first loop (pitch control) was tuned letting the reaction curve overshooting slowly with a longer slow controlled settling down period to avoid the system to oscillate.
2. The second loop (yaw control) was tuned with a tighter reaction time to counter attack the torque created by the front fans.
3. The process was repeated until the reaction curves for yaw and pitch did not show any improvement.

PID Gain Values for Pitch Controller:

P: 6813.01742872752

I: 13170.6613633077

D: 853.093750479044

Filter coefficient(N): 251.511422827374

PID Gain Value for Yaw Controller:

Yaw:

P: 185.640953081057

I: 165.263118768111

D: 51.5096134368126

Filter coefficient(N): 207.04851488926

The gain values are discussed in the conclusion.

Simulating the Operating Sequence

To simulate the normal operation of the helicopter system, a signal generator is added to the virtual model. This generator outputs two signals, one for the pitch and one for the yaw. The sequence follows the user requirements of the automated positioning programme.

Simple PID Control

Figure 4.1 and 4.2 show the pitch and yaw reaction curves against the target coordinates. The interaction of both axes is clearly noticeable. Between 0 and 30 seconds the targeted pitch angle is 0 but at each yaw movement the pitch reacts. The biggest change happens at 40 seconds when the targeted pitch goes from +15 to -15 degrees which causes the yaw to overshoot to nearly 60 degrees.

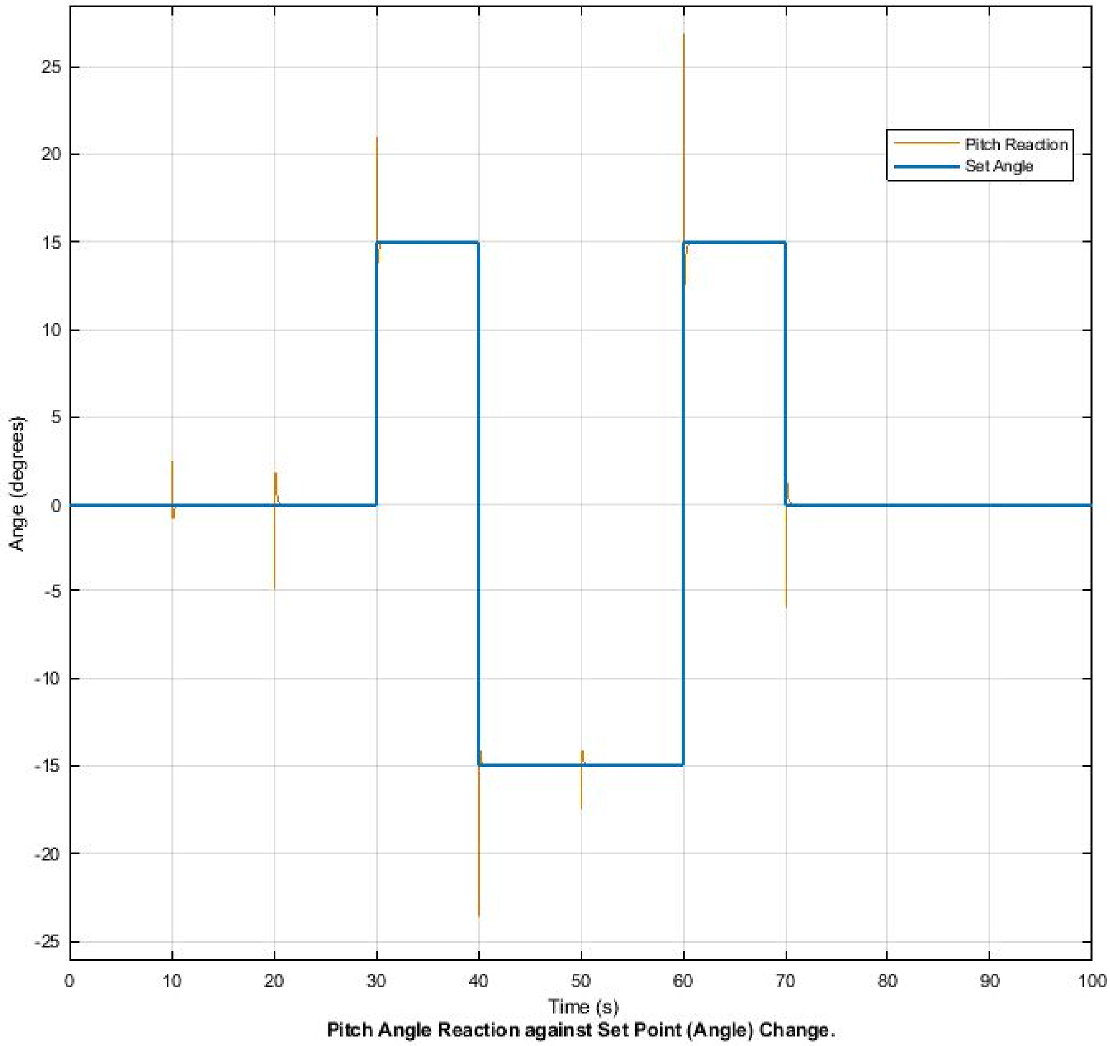

Figure 4.1 Pitch Angle Reaction against Set Point (Angle) Change.

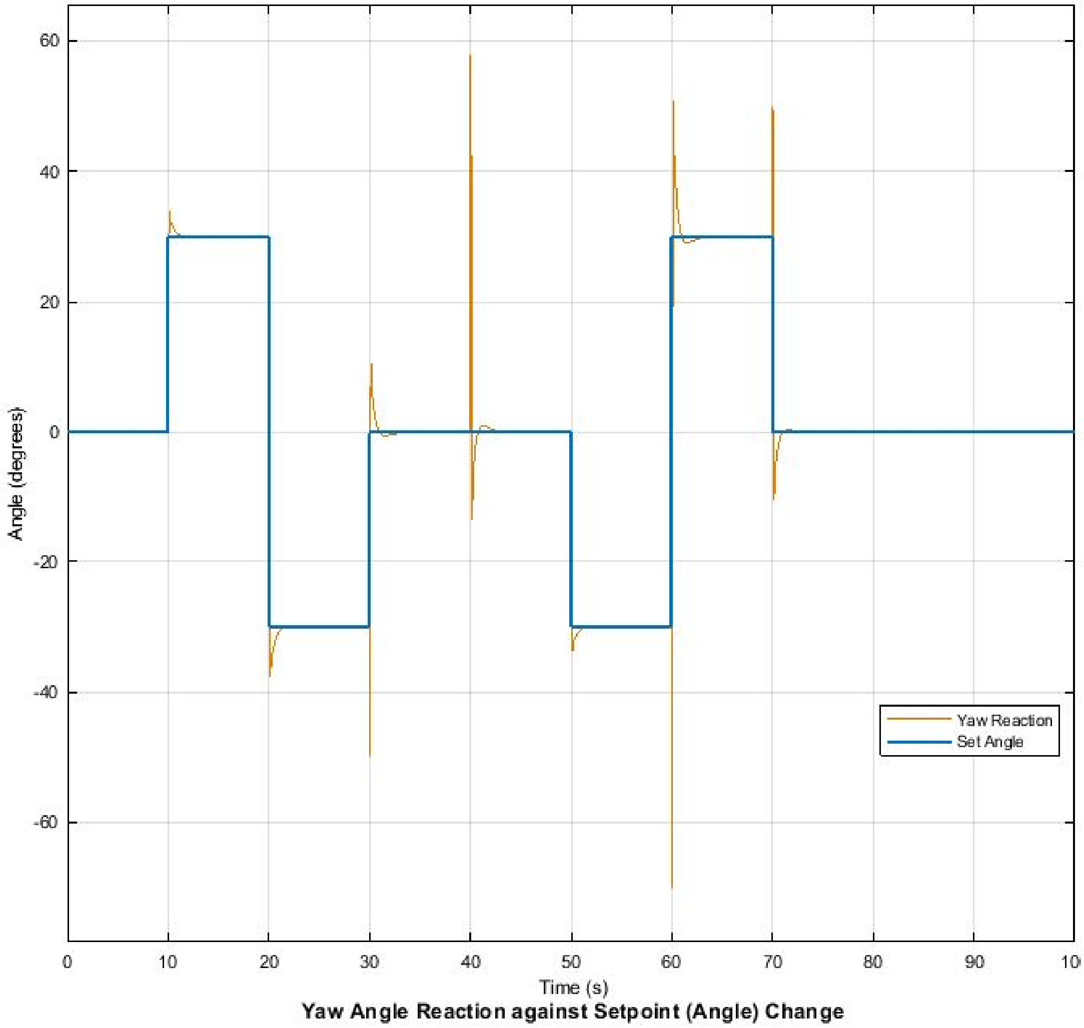

Figure 4.2 Yaw Angle Reaction against Set Point (Angle) Change.

PID Control with Decoupler

The results of the previous simulation clearly demonstrate the necessity of integrating decouplers in the control system as demonstrated in the model in appendix M. Figure 4.3 and 4.4 show the pitch and yaw reaction curves for the system with the same PID tunings but with decouplers. Although both axes still show signs of a dependency, the reactions demonstrate the decoupler are helping to absorb a large part of the impact of the movement.

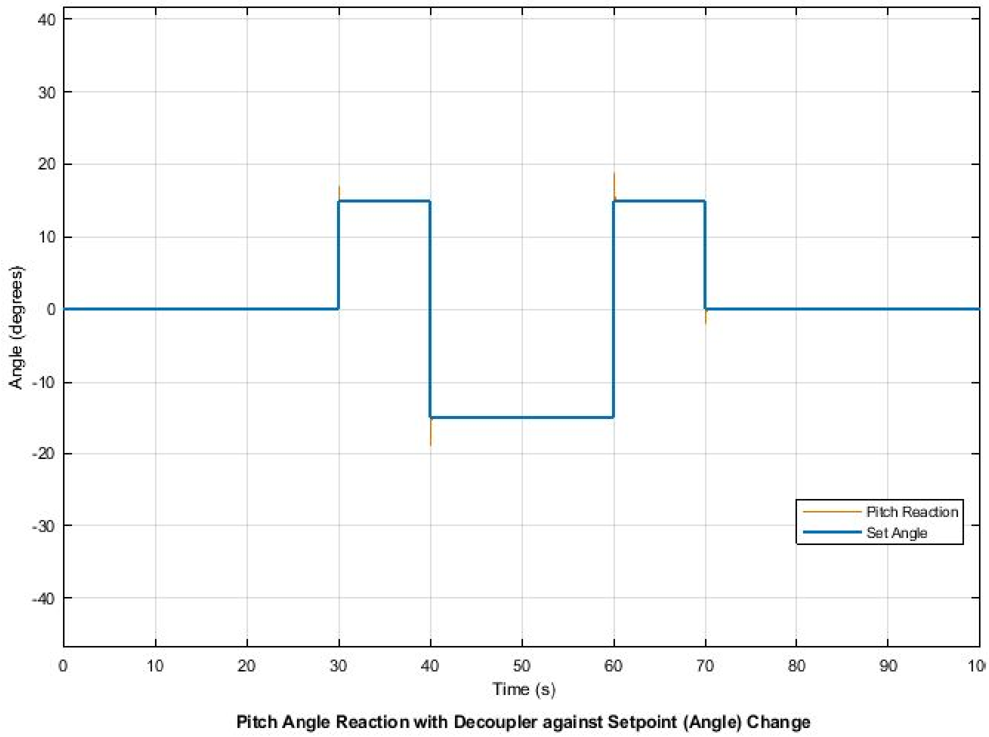

Figure 4.3 Pitch Angle Reaction with Decoupler against Set Point (Angle) Change.

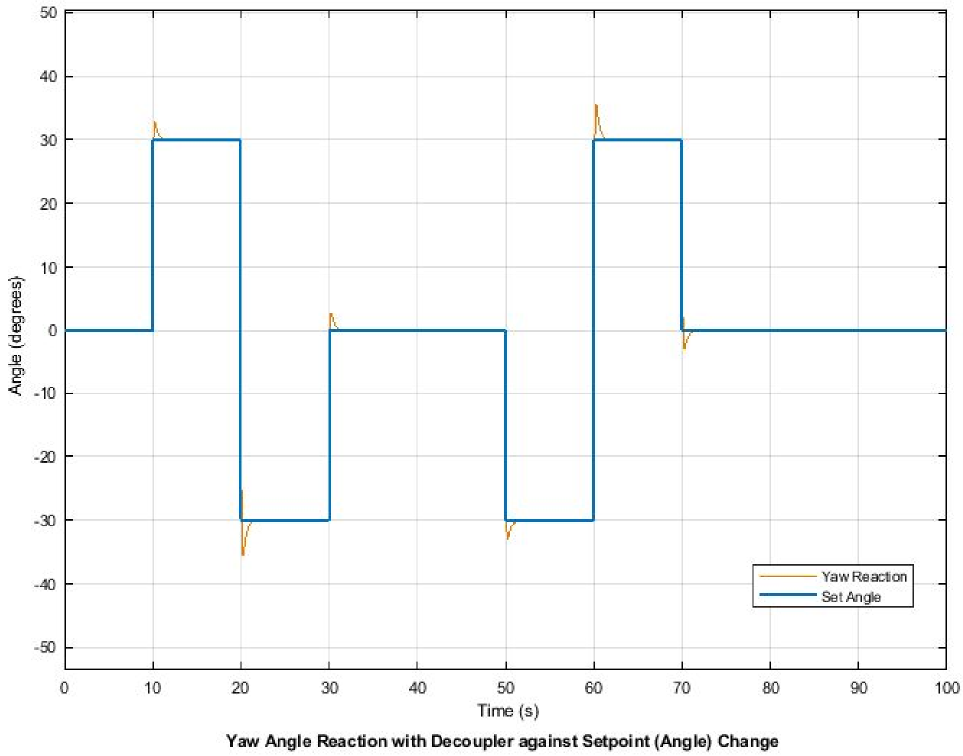

Figure 4.4 Yaw Angle Reaction with Decoupler against Set Point (Angle) Change.

Conclusion

External factors meant the project had to come to a halt as the manufacturing was on going. Most of the mechanical assembly was realised but the electrical cable routing and software implementation and testing were still to be realised.

This report demonstrates the steps taken to answer the requirements of a design brief asking for the development of a 2-DOF helicopter prototype. The application is first described with a product design specification which evolves as the understanding of the problem develops. This allows the mapping the functionalities and selecting the components to meet the specifications of the application. From then, it is possible to derive a mathematical model based on first principles and numerical physical properties from relatable components.

The model of the applications is a "Multi Input Multiple Output" system composed of two PID controllers with decouplers to improve the response. The PID gains extracted are high this is due to the yaw and pitch angle values being fed to the model in degrees rather than the expected radians. The tuning process would therefore need to be done again in a model with a degrees to radians conversion at the input and radians to degrees at the output.

Because of time restrictions, the W-model design methodology was not exactly followed. A more integrated approach was followed where in the conceptual design phase all team members contributed to the development and understanding of the application. Then, in the embodiment design phase, the virtual and physical prototypes were developed simultaneously with problems solved in a multi-disciplinary dimension with a mix of members and sub-teams. It is believed the W-Model would be especially efficient in more complex projects requiring large teams of various backgrounds and with a more important timeframe. At times, some of the actions required by the methodology would have slowed the project development. For instance, the Functional Structure Generation, Classification of Requirements and Functions and Multidisciplinary Dependency Network tasks were condensed in one functional chart rather than separate representations.

References.

HM Government (2016). *Uksi 20161101 en*. [online] Available at: http://www.legislation.gov.uk/uksi/2016/1101/pdfs/uksi_20161101_en.pdf [Accessed 7 Apr. 2020].

Seborg, D., Edgar, T., & Mellichamp, D. (1989). Process dynamics and control. New York: Wiley.

Appendices.

Appendices Content:

Appendix A - Product Design Specifications.
Appendix B - Function Chart.
Appendix C - Electrical Schematic.
Appendix D - Full Assembly.
Appendix E - Plates.
Appendix F - Block Assembly.
Appendix G - Fan Mount.
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Appendix I - Rods.
Appendix J - Factory Acceptance Test.
Appendix K - Functional Test Specifications.
Appendix L - MIMO Controller.
Appendix M - MIMO Controller With Decouplers.

Appendix A - Product Design Specifications.

Mechanical:

Size: The prototype needs to fit within the box provided with internal measurements: 310 x 250 x 225 mm.

Weight: Should be light enough to be carried in the box (below 10kg).

Materials: The base, the housing for the bearings and the housing for the hinge will be made from 6mm thick PVC.

The vertical shaft will be made from 20mm diameter steel. The horizontal body will be made from aluminum rods attached to a yoke system, itself fitted onto the vertical shaft.

Assembly: The prototype will require assembly to allow it to fit in the box.

The fans will be mounted onto frames themselves fitted onto the horizontal rodes. The yoke will be detachable from the main vertical shaft.

The vertical shaft is fitted in bearings themselves mounted onto a platform structure to secure it to the main base whilst allowing yaw movement.

Joints and Motion: The mechanical joints will allow the system to pitch and yaw simultaneously through rotation movements.

Electrical and Electronics:

Power: The system should be able to operate on a 12V DC supply.

Actuators: Two 16 inch rotor fans (1500rpm), and two 80 mm rotor fans (2000rpm).

Sensors: Rotary encoder, fitted to the vertical shaft, for yaw motion monitoring.

Inertial Measurement Unit sensor, attached to the mobile section of the yoke, for pitch motion measurement.

Controller: The system will be controlled by an Arduino Mega (microcontroller: ATmega2560) and a motor drive board.

Display: Information will be displayed on a 16x02 LCD screen.

Buttons: Two control push buttons and one emergency stop.

Operation and Performance:

Automatic Mode: Pitch and Yaw axes (2-DOF) have to be controlled in order to let the helicopter maintain different positions for 10 seconds each in an automated sequence:

1) Pitch = 0º, Yaw = 0º.
2) Pitch = 0º, Yaw = 30º.
3) Pitch = 0º, Yaw = -30º.
4) Pitch = 15º, Yaw = 0º.
5) Pitch = -15º, Yaw = 0º.
6) Pitch = -15º, Yaw = -30º.
7) Pitch = 15º, Yaw = 30º.

Manual Mode: Defined positions can be selected independently through the system interface.

Control technique: Two PID controllers will control pitch and yaw to put the system in position. The system controller should absorb some light disturbance.

Operation Safety: The operational angles will be restricted to an operational angle of 120 degrees yaw and operational angle 90 degrees pitch.

Testing: A MatLab model will be used to determine the system limitations and determine PID parameters values.

The physical prototype will be tested, against the simulated model, thanks to data collected from serial readings from the IMU sensor and encoder.

Functional Test Specifications and Factory Acceptance Test documents will be provided to demonstrate how the operational and safety functions are tested and met.

Reliability: The system should operate with some non-compromising defects.

Environment: The system should operate at a normal room setting: 15 to 25ºC, 50% Relative humidity.

Light physical protection will be provided to protect components from dust and physical access.

Ergonomics and Interface:

Display and buttons: The interface will be operated using two push buttons with live information (live measurements, programme selection, menus…) displayed on the LCD screen.
Assembly: Assembly should be minimal, simple and require a low amount of tools.
User Documentation: This documentation will include the Functional Testing Specifications, Technical specifications, Safe Operation Procedures and Health & Safety Recommendations.
Health and Safety: Warning and safety labels affixed where necessary. Electrical components protected from finger access.
Follow requirements of the "CONSUMER PROTECTION - HEALTH AND SAFETY: The Electrical Equipment (Safety) Regulations 2016" regulations.
Protection grids will be mounted onto fans to protect for insertion of foreign bodies.

Manufacturing Capabilities:

Manufacturing: Limited time with technician and machine shop.
Set kit of components and materials available.
Time frame: 10 Week turnaround time.
Budget: £20 available for additional components and/or parts.