DESIGN, MANUFACTURING AND TESTING OF SHIP DECK MOTION COMPENSATION PLATFORM BY USING STEWART PLATFORM

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Abstract: Unlike the larger ships, the various wave motions have a considerable effect on comparatively smaller ships. The heave, pitch and roll motion of the ship creates many problems like difficulty in safe landing of a helicopter, spilling of valuable fluids, handling of fragile objects, accurate positioning of weapons, etc. Our aim in this project is compensating the motion of the ship by using a Stewart platform. It is a 6 degree of freedom parallel robotic platform. In the project compensating mechanism will function by keeping upper plate stable irrespective of the motion of the base plate or ship. This is done with the help of gyroscopic sensors, actuator, and microcontrollers. The scaled model consists of servo motors as rotary actuators and on experimentation, it is found that it can compensate the pitch and roll of baseplate by an angle of about +20˚ to -20˚ satisfactorily. In actual implementation, linear actuators will be used to take up higher loads and for smoother operations. The project also finds application in steady transferring of goods, for laying foundations for oil rigs. It can be used as stable helideck and can be used by creating a stable bridge for transportation of technicians for maintenance of wind farm.

***Keywords*: Arduino MEGA 2560, Breadboard, Helideck, MPU6050, Rod end, Stewart Platform, 6DOF.**

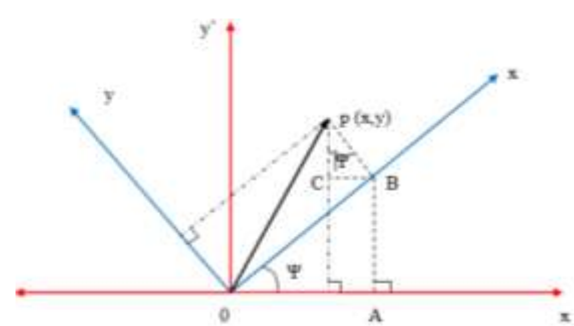
1. INTRODUCTION

In today's world balancing is one of the most important concept used in each and everything we use or we do like balancing of machines, balancing of the engine, balancing of ships etc. Balancing has a large impact on lifestyle, automobile industry, agriculture sector and aerospace or aeronautical industries. The wave motion has a considerable effect on ships or boats. In small ships or boat, there are more vibrations involved due to which it makes the ship or boat unstable. Therefore, we can use modified Stewart platform on the ships or boats to make the helideck stationary. The various motions of ships due to waves create problem while landing of helicopters on the ship deck. So modified Stewart Platform can be used as motion compensation platform to overcome these problems. Basically, Stewart platform is of 6 DOF (six degree of freedom)[1].Motion compensation platform consist of two plates placed one above the other at some height and both the plates are connected with links, above plate is maintained stationary irrespective of lower plate motion and links are actuated by servomotors controlled with the help of Arduino MEGA. As compensation operate, the platform function by remaining stable irrespective of the load applied to it. These are the three linear movements x, y, z (lateral, longitudinal and vertical), and the three rotations pitch, roll, & yaw

2. INVERSE KINEMATIC OF STEWART PLATFORM

The Stewart Platform consists of 2 rigid frames connected by 6 variable length legs. The Platform is considered to be the reference frame work, with orthogonal axes x', y', z'. The Base has its own orthogonal coordinates x, y, z. The Base has 6 degrees of freedom with respect to the Platform.The origin of the Base coordinates can be defined by 3 translational displacements with respect to the Platform, one for each axis. Three angular displacements then define the orientation of the Base with respect to the Platform. A set of Euler angles are used in the following sequence:

A) Rotate an angle ψ (yaw) around the z-axis
B) Rotate an angle θ (pitch) around the y-axis
C) Rotate an angle Φ (roll) around the x-axis



A) Consider the first rotation ψ (yaw) around the z-axis

There is a particular point P on the base plate and getting yaw angle Ψ with respect to z- axis.

$$x' = OA - BC$$

$= x\cos\Psi - y\sin\Psi$
$y' = AB + CP$
$= x\sin\Psi + y\cos\Psi$
$z' = z$

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = R_z\,\Psi \begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad and \quad R_y\theta = \begin{pmatrix} \cos\Psi & -\sin\Psi & 0 \\ \sin\Psi & \cos\Psi & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Fig.2.1 Rotation of base about z-axis

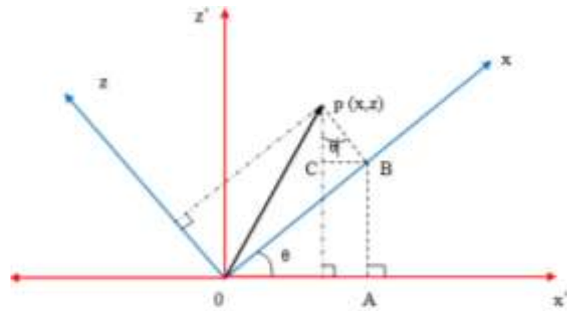


Fig.2.2 Rotation of base about y-axis

B) If we consider the second rotation θ (pitch) around the y-axis:

Considering angle θ with respect to the x-axis.

$x' = OA - BC$
$= x\cos\theta - z\sin\theta$
$z' = AB + CP$
$= x\sin\theta + z\cos\theta$
$y' = y$

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = R_y\theta \begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad and \quad R_y\theta = \begin{pmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{pmatrix}$$

C) And for the third rotation φ(roll) around the x-axis:

Considering angle Φ with respect to z- axis.

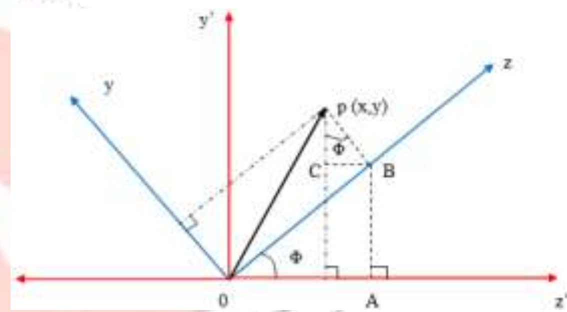


Fig.2.3 Rotation of base about x-axis

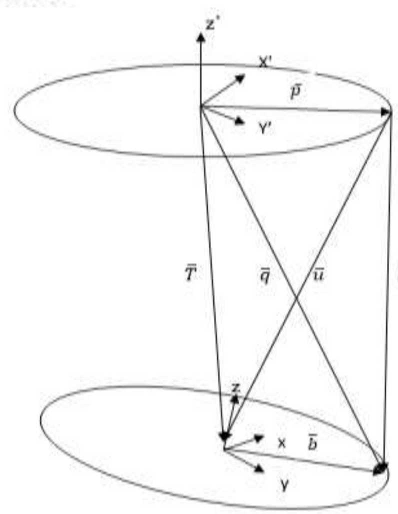
$x' = x$
$y' = AB + CP$
$y' = y\cos\Phi + z\sin\Phi$
$z' = OA - BC$
$z' = z\cos\Phi - y\sin\Phi$

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = R_x\Phi \begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad \text{And} \quad R_x(\Phi) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\Phi & \sin\Phi \\ 0 & -\sin\Phi & \cos\Phi \end{pmatrix}$$

The full rotation matrix of the base relative to the platform is then given by:
${}^bR_p = R_z(\Psi)\ R_y(\theta)\ R_x(\varphi)$

$${}^bR_p = \begin{pmatrix} \cos\Psi\cos\theta & -\sin\Psi\cos\Phi + \cos\Psi\sin\theta\sin\Phi & -\sin\Psi\sin\Phi - \cos\Psi\sin\theta\cos\Phi \\ \sin\Psi\cos\theta & \cos\Psi\cos\Phi + \sin\Psi\sin\theta & \cos\Psi\sin\Phi - \sin\Psi\sin\theta\cos\Phi \\ \sin\theta & -\cos\theta\sin\Phi & \cos\theta\cos\Phi \end{pmatrix}$$

Now consider a Stewart platform:-
The coordinate q_i of the lower anchor point bi with respect to the platform reference framework are given by the equation
$\overline{q_i} = \overline{T} + {}^BR_P \times \overline{b_i}$
Where $\overline{T}$is the translation vector, giving the positional linear displacement of the origin of the Base frame with respect to the Platform reference framework, and $\overline{b_i}$ is the vector defining the coordinates of the lower anchor point b_i with respect to the base framework.
Since $\overline{q_i} = \overline{T} + {}^pR_B \times \overline{b_i} = \overline{p_i} + \overline{l_i}$



So the length of i^{th} leg is given by
$l_i = \overline{T} + {}^pR_B \times \overline{b_i} - \overline{p_i}$
Where $\overline{b_i}$=vector defining the co-ordinate of lower anchor point b_i.
Assume $\overline{u}$ be co – ordinate of base plate center with respect to upper anchor point p_i which is given by

$ui = \bar{T} + pi$.

Since we are using servomotor a further calculation is required to determine the angle of rotation of the servo.

Fig.2.4. Stewart Platform

Where, a=length of the servo operating arm.

A_I are the points of arm on i[th] servo with co-ordinates.

$a = \begin{pmatrix} x_a \\ y_a \\ z_a \end{pmatrix}$ In the base framework.

B_i are the points of rotation of the servo arm with co-ordinates.

$b = \begin{pmatrix} x_b \\ y_b \\ z_b \end{pmatrix}$ In the base framework.

P_i is the point that joints between the operating rods and the platform with co-ordinates

$p = \begin{pmatrix} x_p \\ y_p \\ z_p \end{pmatrix}$ In the base framework.

S=length of the operating leg
α=angle of servo operating arm from horizontal
β=angle of servo arm relative to x-axis

Point A is constrained to be on servo arm but arrangement of servo motor should be such that even and odd motor arm should b reflection of each other.

So for even legs we have

$x_a = a\, cos\alpha\, cos\beta + x_b$

$y_a = a\, cos\alpha\, sin\beta + y_b$

$z_a = a\, sin\alpha + z_b$

And for the odd legs we have,

$x_a = a\, cos(\pi - \alpha)\, cos(\pi + \beta) + x_b$

$y_a = a\cos(\pi - \alpha)\sin(\pi + \beta) + y_b$

$z_a = a\sin(\pi - \alpha) + z_b$

But $sin(\pi - \alpha) = sin\alpha$ and $sin(\pi + \beta) = -sin\beta$

$cos(\pi - \alpha) = -cos\,\alpha$ And $cos(\pi + \beta) = -cos\beta$

Therefore,

$x_a = a\, cos\alpha\, cos\beta + x_b$

$y_a = a\, cos\alpha\, sin\beta + y_b$

$z_a = a\, sin\alpha + z_b$

$\bar{A} = \bar{b} + \bar{a}$

$\bar{a} = \bar{A} - \bar{b}$

$a^2 = (x_a + x_b)^2 + (y_a + y_b)^2 + (z_a + z_b)^2$

$= (x_a^2 + y_a^2 + z_a^2) + (x_b^2 + y_b^2 + z_b^2) - 2(x_a.x_b + y_a.y_b + z_a z_b)$ ------- (2.1)

Now $\bar{l} = \bar{u} + \bar{b}$

$l^2 = (x_u + x_b)^2 + (y_u + y_b)^2 + (z_u + z_b)^2$

$= (x_u^2 + y_u^2 + z_u^2) + (x_b^2 + y_b^2 + z_b^2) + 2(x_u.x_b + y_u.y_b + z_u.z_b)$---- (2.2)

Now $\bar{s} = \bar{u} + \bar{a}$

$s^2 = (x_u + x_a)^2 + (y_u + y_a)^2 + (z_u + z_a)^2$

$= (x_u^2 + y_u^2 + z_u^2) + (x_a^2 + y_a^2 + z_a^2) + 2(x_u.x_a + y_u.y_a + z_u.z_a)$--- (2.3)

From equation (2.1), (2.2) and (2.3)

$s^2 = l^2 - (x_b^2 + y_b^2 + z_b^2) - 2(x_u.x_b + y_u.y_b + z_u.z_b) + a^2$
$- (x_b^2 + y_b^2 + z_b^2 + 2(x_a.x_b + y_a.y_b + z_a z_b) + 2(x_u.x_a + y_u.y_a + z_u.z_a)$

Which is an equation of the form

$L = M\, sin\alpha + N\, cos\alpha$

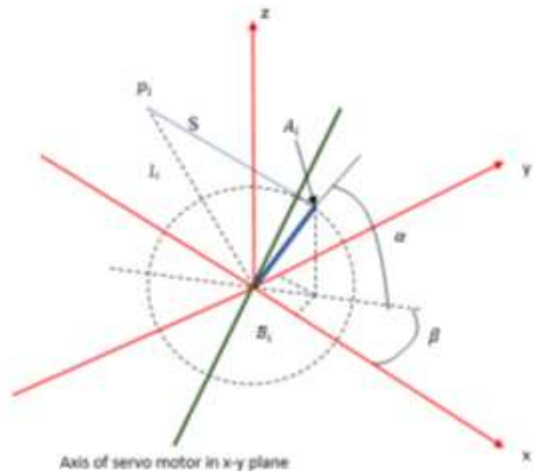


Fig.2.5 Servo angle of Fixed actuator based Stewart

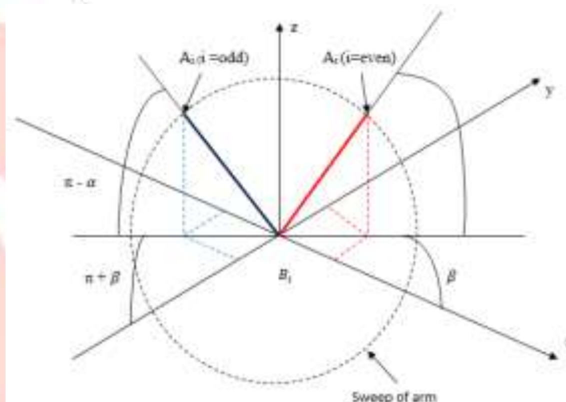
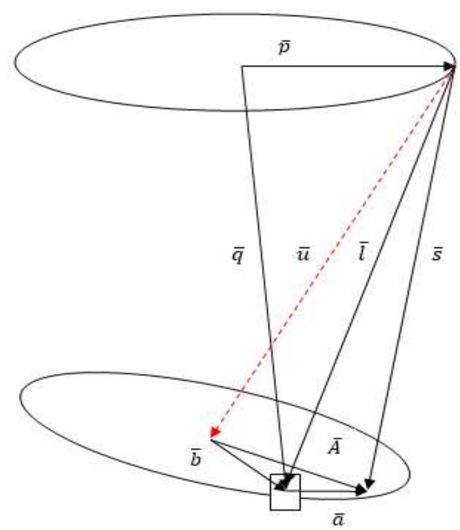


Fig.2.6 Servo arm positioning for compensation



Using the trigonometry for the sum of sine waves

$a\ sin\alpha\ +\ b\ cos\alpha\ =\ c\ sin(x\ +\gamma)$

Where $c\ =\sqrt{a^2+b^2}$ and $tan\gamma\ =\ \frac{a}{b}$

We therefore have another sine function of a with a phase shift of δ

$L\ =\ \sqrt{M^2+N^2}sin(\alpha+\delta)$ Where $\delta = tan^{-1}\frac{N}{M}$

$sin(\alpha+\delta)\ = \frac{L}{\sqrt{M^2+N^2}}$

And $\alpha\ =\ sin^{-1}\frac{L}{\sqrt{M^2+N^2}}\ -\ tan^{-1}\frac{N}{M}$

Where $L\ =\ s^2\ -\ (l^2\ +\ a^2)$

$M\ =\ 2a(z_b\ +\ z_u)$

$N\ =\ 2a[cos\beta(xb\ +\ xu)\ +\ sin\beta(yb\ +yu)\ ]$ ………. [6]

Fig.2.7 Fixed actuator based Stewart Platform kinematics

3. EXPERIMENTS DETAILS AND DESIGN

3.1 Experimental Details:

The setup consists of following parts:

MPU6050: It is a Micro processing unit. It is used for inertia measurement. It contains both gyroscope and accelerometer. It can measure 6 DOF.

Servo Motor: It is an electrical actuator. It takes feedback from Arduino and gets actuated.

Arduino Mega: It is a microcontroller board with 54 input/output pins, a USB connection, a power jack, and a reset button. It contains everything needed to support the microcontroller; simply connect with a USB cable or power it with an AC-TO-DC adapter or battery to get started.

3.2 Design:

A. The length of the link:

Considering the inverse kinematics where we decide the optimum position of servomotor and find out the parameters of motor and length of the link. Assuming the height between the two plates is 150 mm and $\beta = 0(\text{ i.e. arm parallel to x} - \text{axis})$ so by kinematics s= 130 mm

B. The torque of motor:

Torque=force × perpendicular distance.

The standard torque of servomotor is calculated based on 1 inch (2.54cm) of the servo arm.

Therefore,

Perpendicular distance=25.4mm

$\text{Force}\ =\ \frac{(\text{wt. of upper plate + wt. of helicopter})}{6} +\ \text{wt. of links}$

Upper plate:

Material of upper plate acrylic

Density of acrylic= 1190 kg/m^3……………….. [2]

Wt. of upper plate= Volume × density × g

= 14905.16 ×8×10^{-9}×1190×9.81

= 1.392N ~ 5N

Weight of helicopter = 1kg

=9.81N ~ 10 N

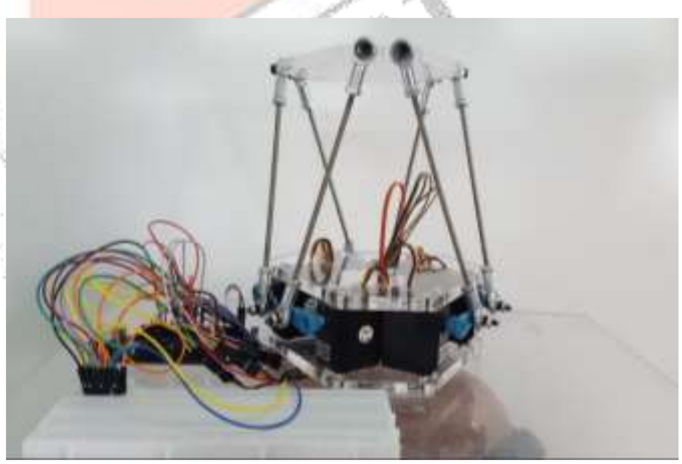


Fig.3.1 Final Product Setup

C. The diameter of the link:

At rest position, when no actuation is present, there can be bending of the link due to the force acting due to the weight of upper plate and helicopter. Considering link of Mild steel.

$$\frac{\sigma_b}{y} = \frac{M}{I_{yy}}$$

Permissible stress σ_b = 155 N/mm^2………….. [3]

$$\frac{155}{\frac{d}{2}} = \frac{2.5\times25.4}{\frac{\pi\, d^4}{64}}$$

D = 1.6099 mm.
Selecting diameter of the rod as 4 mm.

D. The weight of each link:

Considering material as Mild steel
Density of Mild steel = 7850 kg/m^3.................. [4]
Weight of each link = Volume × density × g

$= l \times \frac{\pi d^2}{4} \times 7850 \times 9.81$

$= 130 \times \frac{\pi \times 4^2}{4} \times 7850 \times 9.81 \times 10^{-9}$

= 0.1258 N

Force on each motor = $\frac{(5+10)}{6} + 0.1258$ = 2.6258 N
We are designing for 10N
Therefore, FOS=10/2.6258 = 3.8083
Torque of motor = $10 \times 25.4 \times 10^{-3}$
=0.254Nm
=2.54kg-cm
Therefore selecting digital servo motor of torque above 2.589kg-cm i.e. Futuba S3003 SERVO with 4.5kg-cm torque with dimension (39.9×20.10×36.1) mm………………………… [5]

E. Checking for the thickness of upper plate:

During actuation or at the stationary upper plate may undergo shear failure at the joints.

$\tau_{applied} = \frac{force}{Area} = \frac{15}{projected\ area} = \frac{15}{l \times b}$

$= \frac{15}{10 \times 4} = 0.375\ N/mm^2$

Consider FOS =2 and $\sigma_y = 69\ N/mm^2$ ……….. [2]

$\tau_{permissible} = \frac{\sigma_y}{2 \times fos} = \frac{69}{4} = 17.25\ N/mm^2$

Since $\tau_{permissible} > \tau_{applied}$
So, design safe.

4. COST ANALYSIS

Table 1. Cost Analysis

COMPONENTS	QUANTITY	COST
Acrylic Sheet With Laser Cutting	1	650/-
Arduino Mega	1	800/-
Arduino UNO	1	500/-
Link	6	60/-
MPU 6050	2	400/-
Servo motor	6	1800/-
Nuts and Bolt	12	80/-
Rod Ends	12	1320/-
Total		5610/-

5. SCOPE

i. For carrying the patient in Ambulance comfortably.
ii. It can be used for simulation of ships, cars, and airplane.
iii. It can be used for the position of machining tools where accurate positioning is needed and where disturbances exist.
iv. Thus it finds applications from large scale self-balancing platform for ships to small scale self-aligning cups and spoon for old people.

6. RESULT

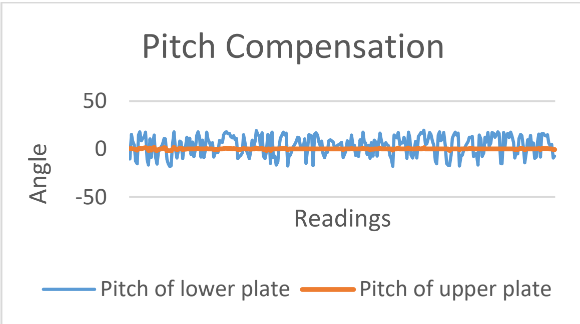


Fig.6.1 Plot of pitch of lower base platform Vs pitch of upper compensated platform

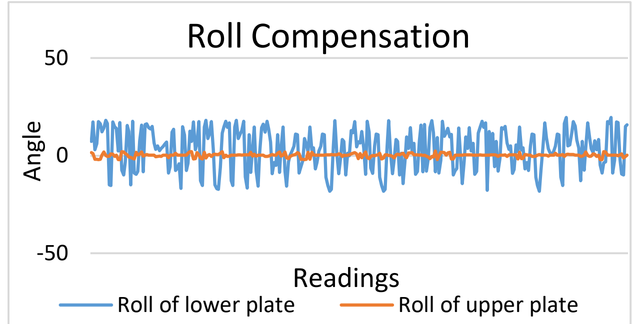


Fig.6.2 Plot of roll of lower base platform Vs roll of upper compensate platform

7. SUMMARY

The work in the report is intended to give a deeper understanding of the 6DOF parallel manipulator known as the Stewart platform, and the possibility of using a Stewart platform for compensation of ship mounted helideck. The Stewart platform for wave compensation is intended to be used as a mounting platform for helideck and act as a stable foundation on the moving ship and thus minimize the movement of the helideck on the ship. The Stewart platform is suitable for the wave compensation application because it has 6 degrees of freedom which is equivalent to the motion of a ship, and thus it can counteract all motions of the ship within a certain range.

8. REFERENCES

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