Building the control signal model for design of 3DOF motion platform of marine simulation system

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Abstract. In this article, the dynamics of a 3DOF motion platform which supports the bridge and imitates the motion of the ship is studied that introduces a new control signal model. This research is based on a Stewart platform in three degrees of freedom (roll, pitch and heave). The platform deck is moved by three frequency-controlled servo drives. A new approach is presented to deal with this issue, namely “the exact control signal model estimation method”. Based on Newton-Raphson iterative method, simulation of this approach is conducted, their demerits and merits are compared in detail. It is concluded that the improved estimation model, when providing good initial iteration values, shows the exact simulation of the nonlinear kinematics of the considered parallel manipulator 3DOF motion platform.

1. Introduction
The ship simulation system is intended to create an exact replica of the cockpit of a modern ship. In this article, the size of the cockpit is designed to be 4x4m and height is 1.95 m. The fully loaded weight of the cockpit is about 1500 kg. Control panel, devices such as Radar/ARPA, ECDIS, Conning ... and other furniture are also equipped. The cockpit is mounted on a moving floor in three degrees of freedom. The motion deck is designed on the basis of Stewart platform. In fact, the application of Stewart platform motion model for transport simulation systems such as aircraft, ships, cars ... is very diverse and rich. In this work, the author directs to the three-step model of parallel three-axis control model based on the rotation of the servo motor with the crank joint connected to the intermediate arm as shown in figure 2.

There are many studies around this type of structure such as [1,3,4,5] studies on reverse dynamics, three-piston geometry, works [3] on dynamic control, learning force. However, only the works [4,5] studied the structure similar to the structure of the proposed article. These constructions allow the approximate calculation of the rotation angle of the αi servo motor so that when the vibration of the simulated floor surface is about ±15°, which is almost the same as the actual movement of a ship, the error is up to 5%. This reduces accuracy in ship motion simulation. The article will focus on building an accurate αi response to future control models, and at the same time conduct simulations to evaluate error values based on the positive kinematic model using Newton-Raphson.

2. Simulation model of three-step freedom ship
The motion model applied for the ship cockpit cabine simulation system is proposed to have 3 degrees of freedom based on the structure of Stewart platform. However, the current common drive structure of this structure is to use a linear-driven piston drive system through an endless screw connecting the shaft
with hydraulic, pneumatic or servo electric motors. In this article, the author investigates a modified structure in which three parallel axes are replaced by three levers that are matched with three rotating arms driven by three servo motors as shown in figure 1,2. Thus the control signal is directly transferred. The movement of the cabine floor is the angle value of the 3 cranks:

\[ \alpha = [\alpha_1 \ \alpha_2 \ \alpha_3]^T \]  

(1)

![Figure 1. Flooring used to attach cabine cockpit.](image)

![Figure 2. Triangular transmission frame.](image)

![Figure 3. Geometric diagram of 3DOF model.](image)

The geometric structure of this model is shown in figure 3, in which \( P_1, P_2, P_3 \) are the three positions on the movable floor surface with articulated arm; \( B_1, B_2, B_3 \) are 3 center points of rotation of servo system / gearbox on fixed floor and \( A_1, A_2, A_3 \) are 3 couplings between lever arm \( b \) and crank \( a \). The two equilateral triangles \( P_1P_2P_3 \) and \( B_1B_2B_3 \) have equal size with each side length \( L = 1255mm \).

In the original position of the movable floor (\( P_1P_2P_3 \)) from the fixed floor (\( B_1B_2B_3 \)) is \( h_z = 458mm \). The cockpit cabine in figure 1 is located at a height of \( h_0 \approx 0 \) from the mobile floor (\( P_1P_2P_3 \)) in figure 2. The size requirements of the three parameters \( a, b, h_z \) are as follows: \( b^2 = a^2 + h_z^2 \), \( A_1P_1 = b = 500mm \); \( B_1A_i = a = 200mm \); \( O_iO = h_z \).
Fixed axis system mounted on mobile floor plane (P1 P2 P3) has x, y, z axes as shown in figure 3,4. With this plane, there are 3 movements generated: rotation around y axis (horizontal shake) is \( \phi \); The rotation around x axis (vertical swing) is \( \theta \) and the sliding motion along the vertical axis is \( z \). Thus, we have the state of the floor as follows: \( \eta = [\phi \ \theta \ z]^T \).

In order to get the position of the mobile floor according to the position of the simulation ship, we have to convert the 3 coordinate axes to the coordinate system mounted on the fixed floor \( (B_1 B_2 B_3) \) with the conversion coordinates matrix. According to document [2] on ship dynamics there are two transverse motion transitions \( \phi \) and shake vertically \( \theta \) of the ship with center of rotation \( O \) with two rotation matrix equations is [2] as follows:

\[
T_r = \begin{bmatrix}
\cos \phi & 0 & -\sin \phi \\
0 & 1 & 0 \\
\sin \phi & 0 & \cos \phi 
\end{bmatrix};
T_p = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \theta & -\sin \theta \\
0 & \sin \theta & \cos \theta 
\end{bmatrix}
\]  

From [2] we obtain the conversion matrix as product \( T_r T_p \). Assuming that the cockpit cabin is located at the center of the floor and a distance of the floor \( h_0 \approx 0 \). We have the coordinates of the three points \( P_i \) on the mobile floor in the original position:

\[
P_{123}(0) = \begin{bmatrix}
\frac{L}{2} & -\frac{L}{2} & 0 \\
\frac{L}{2\sqrt{3}} & \frac{L}{2\sqrt{3}} & -\frac{L}{\sqrt{3}} \\
\frac{L}{2\sqrt{3}} & \frac{L}{2\sqrt{3}} & -\frac{L}{\sqrt{3}} \\
0 & 0 & 0 
\end{bmatrix}
\]  

Combining [2] and [3], we get the coordinates of the three points on the mobile floor according to the coordinates of the axis on the fixed floor will be \( T_r T_p P_{123}(0) \). The third axis conversion is just sliding along the z axis, so we just need to add the z coordinates of the three points with an equal value of \( z_t \).

3. The reverse kinematic model determines the rotation angle of the servo motor

The reverse kinematic model is important for the control problem to determine the rotation angle of each motor shaft \( \alpha_i \) \((i = 1,2,3)\) from the inclination, sway and relative height data from the model. 3D simulator of the ship is vector \( \eta \). With the initial height of the moving floor center compared to the fixed floor is \( h_z \), so the center \( O \) of the floor is \( z_t = h_z + z \) and has the coordinates: \( O = [0 \ 0 \ h_z + z]^T \) in a fixed plane. Combined with the axis transformations performed in item 2, we get the coordinates of the points \( P_{123} \) will have the following form [4]:

Figure 4. Crank and arm of 1 axis.
The Jacobian matrix of function $f$ is found by taking the separate derivative for each variable of $f$. We need the $z$ values of the connection points as the last row of the matrix [4]. According to equation [5], we have the rotation angle of each axis to be approximated as follows:

$$a_i = \sin^{-1}\left(\frac{z_i-h_z}{a}\right)$$ (5)

However, due to the limitations of [3] as mentioned above, the next section we will look for a more accurate $a_i$ calculation formula. First, from figure 4, we have the coordinates $B_i$ of the fixed floor surface and the point $A_i$ is the axis hinge joint as [6] below:

$$B_{123} = \begin{bmatrix} \frac{L}{2} & -\frac{L}{2} & 0 \\ \frac{\sqrt{3}L}{2} & \frac{\sqrt{3}L}{2} & 0 \\ \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 \\ 0 & 0 & 0 \end{bmatrix} ; A_{123} = \begin{bmatrix} \frac{L}{2} & 0 & 0 \\ \frac{\sqrt{3}L}{2} & 0 & 0 \\ 0 & \frac{\sqrt{3}L}{2} & 0 \\ 0 & 0 & \frac{\sqrt{3}L}{2} \end{bmatrix}$$ (6)

Knowing the coordinates of points $P_i$ from [4] and $B_i$ from [6] we will calculate the lengths of the edges $O_0 P_i$ and $B_i P_i$. Applying the theorem of cosine function with the triangles $O_0 B_i P_i$ and $P_i B_i A_i$, we compute the angles $\delta_{1i}, \delta_{2i}$. From there we calculate the exact angle $a_i$ as equation [7]:

$$a_i = \pi - (\delta_{1i} + \delta_{2i})$$ (7)

Therein:

$$\delta_{1i} = \cos^{-1}\left(\frac{c - x_i^2 + y_i^2}{x_i^2 + (c - x_i^2 + y_i^2)^2}\right) ; \delta_{2i} = \cos^{-1}\left(\frac{a^2 + x_i^2 + (c - x_i^2 + y_i^2)^2 - b^2}{2a\sqrt{x_i^2 + (c - x_i^2 + y_i^2)^2}}\right) ; c = O_0 B_i = \frac{L}{\sqrt{3}}$$ (8)

4. **Verify by the positive dynamics model**

Constructing a dynamic kinematic model helps us determine the actual tilt, sway and relative height of the model motion from the rotation angle of the three $a_i$ engines to compare with the data of tilt, sway and elevation 3D simulation word is vector $\eta$. To build upon the positive kinematic model, we use the Newton-Raphson method. The length $A_i P_i = b$, from the coordinates of $A_i$ and $P_i$ in [4,6], we calculate $|A_i P_i|^2 = b^2$ and set the function $f_i$ of the form $f_i = [f_1 f_2 f_3]^T$ in which the hidden $\phi, \theta, z$ is unknown:

$$f_i = (x_{P_i} - x_{A_i})^2 + (y_{P_i} - y_{A_i})^2 + (z_{P_i} - z_{A_i})^2 - b^2$$ (9)

Because $f_i$ contains more than one variable, the derivative of $f_i$ used in the Newton-Raphson method is found by taking the separate derivative for each variable of $\eta$. $J$ is the Jacobian matrix of function $f_i$ with variable $\eta$ calculated as [10] below:

$$J_{ij} = \frac{\partial f_i}{\partial \eta_j} (\eta) = \begin{bmatrix} \frac{\partial f_1}{\partial \phi} & \frac{\partial f_1}{\partial \theta} & \frac{\partial f_1}{\partial z} \\ \frac{\partial f_2}{\partial \phi} & \frac{\partial f_2}{\partial \theta} & \frac{\partial f_2}{\partial z} \\ \frac{\partial f_3}{\partial \phi} & \frac{\partial f_3}{\partial \theta} & \frac{\partial f_3}{\partial z} \end{bmatrix} ; i, j = 1, 2, 3$$ (10)
From there, the unknowns in $\eta$ will be calculated using the equation: 

$$\eta_{n+1} = \eta_n - [J(\eta_n)]^{-1} f(\eta_n);$$

with the first condition $\eta_0 = [\phi_0, \theta_0, z_0]^T$. The result of this iterative algorithm is accurate enough that the precision definition parameter $\varepsilon$ must be predefined small enough: $|f_i(\eta)| \leq \varepsilon$. From [9], [10] we finally have the algorithm flowchart as shown in figure 5.

5. Simulation results

The simulations were performed with scenarios of only horizontal shaking, vertical shaking only, vertical sliding only, and mixed motion of figure 5,6.

![Figure 5. Newton-Raphson algorithm.](image)

![Figure 6. System simulation diagram on Matlab/Simulink.](image)

The response signals consist of three $\alpha_i$ rotation angles of the three servos (alpha1, alpha2, alpha3); input signals received from the ship's 3D simulation part include three motion $\eta$ (roll, pitch, heave); deviations between input signal and signal after "Forward Model" model (sum1, sum2, sum3) figure 7, 8, 9, 10.

![Figure 7. Simulation results when there is only horizontal swing ($\Phi$-roll).](image)

![Figure 8. Simulation results when there is only vertical shake ($\theta$-pitch).](image)
For $\varepsilon = 10^{-6}$ and select the initial iteration value $\eta_0^T = [0 \ 0 \ 0]^T$ from the simulation results of figures 7, 8, 9, 10 we find the error with This new model does not exceed $0.18^0 / 17.5^0 \approx 1\%$, and we also draw an important conclusion for the optimal range of rotation angle values for servo control, within the linear region is $\alpha_i = \pm 70^0$ corresponding to the limit of roll movements: $\pm 17.5^0$, pitch: $\pm 15^0$, heave: $\pm 190$mm.

6. Conclusion
The simulation results in section 5 show the accuracy of choosing the appropriate control signal model, which contributes to the task of reflecting the honesty in the ship's motion simulation, creating a real feeling for trained people. However, the equation [7,8] for calculating $\alpha_i$ angle is also more complicated than in other constructions, this can lead to real-time degradation of the 3D simulation system. The evaluation of this criterion involves the process of algorithm synthesis and the selection of a set of servo motors, so it is necessary to study it in another project.

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