Analytical description and Numerical Simulation of Platform leveling mechanism

Mootaz Ebraheem Aboelnor (✉ mootaz_aboelnor@mtc.edu.eg)
Military Technical College  https://orcid.org/0000-0002-0819-1564

Research Article

Keywords: Platform leveling, loop-closure kinematics, Tilt-Pitch mechanism

Posted Date: May 17th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1480228/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License
Analytical description and Numerical Simulation

Of Platform leveling mechanism

Mootaz E. Abo_Elnor∗

∗Assoc. Prof., Mechanical Equipment Dept., Military Technical College, Cairo, Egypt.

Mootaz_aboelnor@mtc.edu.eg

Abstract

Design methodology of moving platform leveling mechanism is introduced based on operational limitation of ground level within tilt and pitch angles of “-2° to +2°” referenced to horizontal plane. Three point support platform leveling mechanism is designed such that it contains moving base (bottom platform), levelled platform (top platform) and leveling linkages (for tilt and pitch orientation restore). The proposed leveling mechanism operates such that leveling achieved by a sequential angular displacement of tilt link and pitch link. An analytical kinematics model based on loop-closure constraint equations is proposed describing the relation between platform tilt - pitch due to ground level status and corresponding tilt link and pitch link angular displacement to restore the top platform level parallel to reference horizontal plane. A 3D CAD model of the proposed leveling mechanism is constructed and a numerical simulation of tilt and pith links angular displacement to restore top platform leveling for different moving base orientation due to ground leveling status is carried out to validate the proposed mechanism kinematics and analysis of mechanism behavior while restoring top platform leveling.

Keywords   Platform leveling, loop-closure kinematics, Tilt-Pitch mechanism

Highlights
1. Introduction

Platform orientation and leveling control is one of the control means objectives in different applications such in parallel and leveling mechanisms which shown extensively in industrial, medical and defense applications. Leveling of moving platforms is important in VTOL aircraft application as they cannot land safely on slopped or uneven terrain [1]. Platform leveling used on ships as embarked helicopter to compensate for the rolling and pitching movements caused by the waves is important in order to compensate for simulators dynamics [2]. In other hand leveling of transport vehicles loading platform is one of the important issues for transportation safety [3]. In mechanical equipment applications such as modern feller-bunchers and graders; platform leveling system is designed taking into consideration ground slope for better efficiency of such equipment [4, 5]. High-precision horizontal platform is required in some applications such in vehicle-mounted radars, artillery launchers and gravity pressure piling machines. For heavy loads of such machines; precise control system is mandatory [6]. Design of platform leveling mechanism is done in sequential stages. In first stage; platform leveling limitation in a specific application is considered. In second stage; linkage design of leveling mechanism and kinematics analysis is carried out. In third stage; forces and dynamics are consider. In forth stage; control system required to fulfill platform performance is applied. In this study forward kinematics analysis of a proposed platform leveling mechanism is carried out as a preliminary step in moving platform leveling design.

2. Kinematics analysis of leveling mechanism
As illustrated in figure 1; the proposed platform leveling mechanism consists of target levelled platform (denoted by spherical joints $S_1, S_2, S_3$), moving base (denoted by spherical joint $S_1$ and revolute joints $R_1, R_2$), tilt links ($r_2$ and $r_3$) and pitch links ($p_2$ and $p_3$). The DOF of this levelling mechanism can be obtained using Grüber’s formula [7] as follow;

$$F = d(n - g - 1) + \sum_{i=1}^{g} f_i$$  \hspace{1cm} (1)

Where:

- $d$.. number of DOF in space = 6
- $n$.. number of links including the frame = 6
- $g$.. number of joints = 7
- $f_i$.. DOF of joint $i$

$$F = 6(6 - 7 - 1) + 15 = 3$$

The shown model can be described as two kinematics loops which are RRSS (identified as $R_2 R_3 S_2 S_1$) and RSSR (identified as $R_1 S_4 S_3 P_1$) where R stands for revolute joint and S stands for spherical joint and $P_1$ is the middle of the link between spherical joints $S_1$ and $S_2$.

As obtained by Equation (1); the number of degrees of freedom DOF of this platform leveling mechanism is three. While in some cases a link can perform rotation around its own axis, this rotation is not affecting the performance of the mechanism [8]. In this proposed mechanism rotation of link $p_3$ (between the two spherical joints $S_4$ and $S_3$) around its own axis is a non-effected degree of freedom and based on this fact; the proposed platform leveling mechanism is of two DOF. Kinematics of parallel manipulators based on rotation and translation matrix is applied in different applications.
[9-13] while in some applications loop-closure constraints equation is used in solving kinematics analytically [8, 14].

2.1 Loop-Closure Equations

The platform leveling will achieved by a sequential acting of the two DOF means, the first DOF is the rotation of link \( r_2 \) around revolute joint \( R_2 \) causing the platform to perform a tilt motion supported on joint \( S_1 \) and joint \( S_3 \) while the second DOF is the rotation of link \( p_2 \) around revolute joint \( R_1 \) causing the platform to perform a pitch motion supported on joint \( S_1 \) and joint \( S_2 \). The most appropriate kinematics analytical for such case is by using loop-closure constraint equations.

Loop-closure constraint equation for platform tilt

Using trigonometric relations for the closed-loop \( r_2 r_3 r_4 r_1 \); forward kinematic relation of platform tilt angle “\( \mu \)" due to active link \( (r_2) \) angular displacement “\( \theta_2 \)" is obtained as follow:

\[
\begin{align*}
  r_2 \cos \theta_2 + r_1 &= r_3 \cos \theta_3 + r_4 \cos \theta_4 \\
  r_2 \sin \theta_2 + r_3 \sin \theta_3 &= r_4 \sin \theta_4 \\
  r_3 \cos \theta_3 &= r_1 + r_2 \cos \theta_2 - r_4 \cos \theta_4 \\
  r_3 \sin \theta_3 &= r_4 \sin \theta_4 - r_2 \sin \theta_2 \\
  r_3^2 \cos^2 \theta_3 &= r_1^2 + r_2^2 \cos^2 \theta_2 + r_4^2 \cos^2 \theta_4 + 2r_1 r_2 \cos \theta_2 - 2r_1 r_4 \cos \theta_4 - 2r_2 r_4 \cos \theta_2 \cos \theta_4 \\
  r_3^2 \sin^2 \theta_3 &= r_4^2 \sin^2 \theta_4 + r_2^2 \sin^2 \theta_2 - 2r_2 r_4 \sin \theta_2 \sin \theta_4 \\
  r_3^2 &= r_1^2 + r_2^2 + r_4^2 - 2r_2 r_4 \cos \theta_2 \cos \theta_4 - 2r_2 r_4 \sin \theta_2 \sin \theta_4 + 2r_1 r_2 \cos \theta_2 - 2r_1 r_4 \cos \theta_4 \\
  2r_2 r_4 \cos \theta_2 \cos \theta_4 + 2r_2 r_4 \sin \theta_2 \sin \theta_4 + 2r_1 r_4 \cos \theta_4 &= r_1^2 + r_2^2 + r_4^2 - r_3^2 + 2r_1 r_2 \cos \theta_2
\end{align*}
\]
\[ A = 2r_z r_4 \sin \theta_2 \]
\[ B = 2r_4 (r_2 \cos \theta_2 + r_1) \]
\[ C = r_1^2 + r_2^2 + r_4^2 - r_3^2 + 2r_1 r_2 \cos \theta_2 \]
\[ A \sin \theta_4 + B \cos \theta_4 = C \tag{8} \]
\[ \frac{A}{\sqrt{A^2 + B^2}} \sin \theta_4 + \frac{B}{\sqrt{A^2 + B^2}} \cos \theta_4 = \frac{C}{\sqrt{A^2 + B^2}} \]
\[ \cos \alpha \cos \theta_4 + \sin \alpha \sin \theta_4 = \frac{C}{\sqrt{A^2 + B^2}} \]
\[ \cos(\theta_4 - \alpha) = \frac{C}{\sqrt{A^2 + B^2}} \]
\[ \alpha = \tan^{-1} \left( \frac{A}{B} \right) \]
\[ \theta_4 = \cos^{-1} \left( \frac{C}{\sqrt{A^2 + B^2}} \right) + \alpha \]
\[ \theta_4 = \cos^{-1} \left( \frac{C}{\sqrt{A^2 + B^2}} \right) + \tan^{-1} \left( \frac{A}{B} \right) \]
\[ \theta_0 = \tan^{-1} \left( \frac{h_0}{l_0} \right) \]
\[ \mu = \cos^{-1} \left( \frac{C}{\sqrt{A^2 + B^2}} \right) + \tan^{-1} \left( \frac{A}{B} \right) - \tan^{-1} \left( \frac{h_0}{l_0} \right) \tag{9} \]

The only unknown in Equation (9) is the link angular displacement \( \theta_2 \).

\[ \theta_{\text{tilt}} = \theta_2 - \theta_0 \]

Where \( \theta_{\text{tilt}} \) is angular displacement of link \( r_2 \) with respect to mechanism moving base.
Loop-closure constraint equation for platform pitch

Similar to forward kinematic relation of platform tilt angle “$\mu$” due to active link angular displacement “$\theta_2$” described in the previous section by Equation (9); the forward kinematic relation of platform pitch angle “$\delta$” due to active link ($p_2$) angular displacement “$\phi_2$” can be obtained as follows:

\[ h_1 = h_0 + \frac{r_4}{2} \sin \mu \]

\[ \Delta r_4 = \frac{r_4}{2} (\cos \mu - 1) \]

\[ \psi_3 = \tan^{-1} \left( \frac{\Delta r_4}{p_3} \right) \]

\[ p_3' = p_3 \cos \psi_3 \]

\[ \phi_4 = \cos^{-1} \left( \frac{C'}{\sqrt{A'}^2 + B'} \right) + \tan^{-1} \left( \frac{A'}{B'} \right) \]

\[ \phi_0 = \tan^{-1} \left( \frac{h_1}{l_1} \right) \]

\[ A' = 2p_2p_4 \sin \phi_2 \]

\[ B' = 2p_4(p_2 \cos \phi_2 + p_1) \]

\[ C' = p_1^2 + p_2^2 + p_4^2 - p_3'^2 + 2p_1p_2 \cos \phi_2 \]

Platform pitch angle $\delta = \phi_4 - \phi_0$

\[ \delta = \cos^{-1} \left( \frac{C'}{\sqrt{A'}^2 + B'} \right) + \tan^{-1} \left( \frac{A'}{B'} \right) - \tan^{-1} \left( \frac{h_1}{l_1} \right) \]  \hspace{1cm} (10)

The only unknown in Equation (10) is the link angular displacement “$\phi_2$”
\[ \phi_{pitch} = \phi_2 - \phi_0 \]

Where \( \phi_{pitch} \) is angular displacement of link \( p_2 \) with respect to mechanism moving base.

### 2.2 Analytical simulation of tilt-pitch platform leveling mechanism

Geometrical parameters of the presented platform mechanism shown in figure 2 and figure 3 is listed in Table [1].

Analytical simulation of platform tilt closed-loop forward kinematics is presented based on active link \( r_2 \) angular displacement “\( \theta_{\text{tilt}} \)” of a range between \( (0^\circ \text{ to } +30^\circ) \) to perform platform tilt with respect to reference horizontal plane. Platform tilt angle “\( \mu \)” with respect to reference horizontal plane is found to be of the range between \( (-2^\circ \text{ to } +2^\circ) \) as shown in Figure 4. As shown in the figure the platform tilt angle “\( \mu=0^\circ \)” as the tilt link angular displacement “\( \theta_{\text{tilt}} = 15^\circ \)”.

To perform platform leveling based on sequential operation of platform tilt and pitch, taking into consideration platform tilt angle “\( \mu=0^\circ \)”, analytical simulation of platform pitch closed-loop forward kinematics is presented based on active link \( p_2 \) angular displacement “\( \phi_{pitch} \)” of range between \( (-5^\circ \text{ to } +35^\circ) \) to perform platform pitch with respect to reference horizontal plane. Platform pitch angle “\( \delta \)” is found to be of the range between \( (-2^\circ \text{ to } +2^\circ) \) as shown in Figure 5. As shown in the figure the Platform pitch angle “\( \delta=0^\circ \)” as the pitch link angular displacement “\( \phi_{pitch} = 15^\circ \)”.

### 3. Numerical simulation of tilt-pitch platform leveling mechanism

The target of the proposed platform leveling mechanism is to maintain the levelled platform parallel to the reference horizontal plane when the orientation of the moving base differ from the reference horizontal plane within range of \( (-2^\circ \text{ to } +2^\circ) \) in both tilt and pitch. To validate results obtained by numerical simulation discussed in the previous section in this article and obtain full range
of angular displacement required by tilt and pitch rotate links; a 3D CAD model is constructed as shown in Figure 6.

The model consists of moving base, levelled platform, tilt rotate link, pitch rotate link, connection links and joints. A numerical simulation of four possible orientations range of the moving platform referred to the reference horizontal plane, table [2], is carried out considering levelling sequence is such that acting of tilt rotate link until tilt angle “μ” is set to zero then acting of pitch rotate link until pitch angle “δ” is set to zero as “μ=0°” and “δ=0°” is the objective to restore platform level.

Snapshots of numerical simulation no. 5 in Table [2] is illustrated in Figure 7 in which proposed mechanism restore platform level as moving base subjected to inclination with tilt angle of -2° and pitch angle of +2° referred to reference to horizontal plane.

4. Results and discussion

Results of simulations no. (1, 2, 3, 4) are illustrated in figure 8. The levelled platform is initially parallel to the reference horizontal plane then the moving base rotates around pitch axis by angle of “+2° “as shown in Figure 8(a). As the simulation proceeds; pitch link rotates by “-19° “to restore platform level.

In Figure 8(b) the moving base rotates around pitch axis by angle of “-2° “. As the simulation proceed; pitch link rotates by “+18° “to restore platform level. Considering platform pitch within the range of “-2° to +2° “shown in both Figure 8(a) and Figure 8(b); the total range of pitch link rotation is (18°+19°=37°).

Same result obtained using analytical solution illustrated in Figure 5. By introducing initial tilt of moving base by “+2° “; Figure 8(c) illustrates the simulation results to restore platform levelling in which some pitch angular displacement introduce to the platform (about +1° ) while the tilt rotate
link rotates by “-15°”. In this simulation to restore the introduced pitch angular displacement; the pitch link rotates about “+5°”. By introducing initial tilt of the moving base by “-2°”, Figure 8(d) illustrates the simulation results to restore moving platform levelling in which some pitch angular displacement introduce to the platform (about -1°) while the tilt rotate link rotates by “+15°”. In this simulation to restore the introduced pitch angular displacement; the pitch link rotates about “+7°”. This means that pitch correction will not introduce tilt angular displacement to the platform while tilt correction will do introduce pitch angular displacement to the platform.

Based on the previous observation; platform levelling is to be obtained by sequential activation of tilt link rotation then pitch link rotation.

Results of simulations no. (5, 6, 7, 8) are illustrated in figure 9 for different probability combination of moving base tilt and pitch. As listed in table [2]; in simulation no. 5 the moving base subjected to tilt rotation with angle “-2°” and pitch rotation with angle “+2°”. During rotation of tilt link to restore platform leveling; pitch angular displacement introduce to the levelled platform reducing pitch deflection to “+1°” instead of “+2°” as shown in figure 9(a). Same observation can be obtained by simulation no. 6 in figure 9(b). As shown in Figure 9(c) the introduced pitch angular displacement, while restoring tilt leveling, is about “+3°” while in Figure 9(d) the introduced pitch angular displacements about “-3°”.

As a conclusion from Figure 9, in order to restore the levelled platform for moving base tilt and pitch angles of “-2° to +2°”, the angular displacement of tilt link should be from “-15° to +15°” and angular displacement of pitch link should be from “-29° to +25°” and the introduced pitch angular displacement, while restoring tilt leveling, is about “±3°”.
5. Conclusion

A kinematics analytical model is proposed based on loop-closure constraint equations in order to obtain tilt link and pitch link angular displacements required to restore the levelled platform parallel to reference horizontal plane as the moving base tilt and pitch due to ground leveling status with respect to the reference horizontal plane. A 3D model is constructed and a numerical simulation is carried out to validate the proposed kinematics analytical model and obtain possible operating range of leveling mechanism rotate links. Simulation results validate the proposed leveling mechanism kinematics considering the sequential operation of tilt link then pitch link rotation as a consequence of introducing pitch angular displacement to the platform while restoring tilt deflection of the platform. For a three point support leveling mechanism; restoring of platform tilt deflection should be carried out first (to account for the introduced pitch angular displacement of the platform during restoring tilt deflection) then restoring of platform pitch deflection is to be carried out to completely restore the platform level.

Availability of data and materials

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests

Funding

Not applicable

Authors' contribution

The author declare that modeling, simulation and analysis along with conclusion remarks in this study are done by himself.

Acknowledgements
References


Figure 1

Kinematics diagram of the RRSS-RSSR leveling mechanism
Figure 2
Kinematics diagram of platform tilt

Figure 3
Kinematics diagram of platform pitch
Figure 4

Relation between platform tilt angle “μ” and tilt link angular displacement “θ_{tilt}”
Figure 5

Relation between platform pitch angle \( \delta \) and Pitch link angular displacement \( \Phi_{\text{pitch}} \)
Figure 6

3D model representing platform assembly to moving base and levelling means

(a) Initial status; platform leveled
(b) Moving base Tilt -2°, Pitch +2°
(c) Tilt link rotates to restore platform tilt
(d) Pitch link rotates to restore platform pitch

Figure 7

3D model (back view) representing sequence of simulation no. 5
Figure 8

Driving links angular displacement to restore platform levelling
Figure 9

Driving links angular displacement to restore platform levelling