KINEMATIC-BASED CONTROL OF A 2-DOF 1U-2RSS BALANCING TABLE

Quang Huu Ta1*, Thanh Son Nguyen1, Dinh Quan Nguyen2
1Military Institute of Mechanical Engineering;
2Le Quy Don Technical University

Abstract
The paper presents the design of a kinematic-based control system of a two degree of freedoms (2-DOF) balancing table with parallel structure of 1U-2RSS. This system is expected to control heavy payloads (up to 100 kg in weight) and can maintain the orientation in the horizontal plane while is being mounted on a mobile vehicle floor. Simulation results on software as well as testing in practice show that the controller can give a good response in maintaining the orientation of the balancing table around its equilibrium pose with respect to the horizontal plane.

Keywords: Balancing system; parallel mechanisms.

1. Introduction
Nowadays, less degree of freedoms manipulators have appeared in many robotic applications such as industrial applications as well as service, social and medical applications. One of the most popular use cases are 2-DOF robotic systems. Several notable applications can be listed such as the Canterbury tracker [1] which utilizes a 2-DOF serial manipulator to drive an antenna in tracking targets, or the 2-DOF agile eye (a 2-DOF spherical parallel manipulator) [2]-[4] which consists of five revolute joints whose axes are intersected at the center point of the eye (or the mobile platform). Systems similar to that of the agile eye system where all the joint axes are intersected at the center pivot point of the universal joint can also be listed such as in [5] - [8].

In a previous study [12], the kinematic analysis of a 2-DOF 1U-2RSS balancing table was presented in which we have shown the computation of the kinematic models, the feasible workspace as well as the problem of selecting suitable design geometric parameters. However, we have not addressed the control of such mechanism system.

In this paper, we focus on developing the control system for the 2-DOF balancing table based on its kinematics and verifying it from simulation and experiment test cases. The paper is organized as follows: Section 2 will present the design of the control system and simulation results using Matlab/Simulink. Section 3 will present the practical results of testing the balancing table on a static platform and on moving vehicles.

* Email: taquanghuuvcg@gmail.com

https://doi.org/10.56651/lqdtu.jst.v14.n03.446
2. Control system design for the 2-DOF balancing table

Fig. 1 shows a 3D model of the 2-DOF balancing table [12]. It contains one universal joint acting as the main pivot point for the top table and two identical legs that support and rotate the table. Each leg has one revolute joint, one spherical joint that connects the two links of the leg and one spherical joint that connects the leg to the moving table. In this design, the system has two DOFs in the task space which are the two orientation constrained by the universal joint (located at the origin O). By moving the two motors, one can change the orientation of the table around the axes X and Y by $\theta_x$, $\theta_y$ respectively.

The inverse kinematic solution of the balancing table can be found in [12]. And its inverse velocity kinematic model was also computed as follows:

$$
\begin{bmatrix}
\theta_1 \\
\theta_2
\end{bmatrix} = J^{-1} \begin{bmatrix}
\dot{\theta}_x \\
\dot{\theta}_y
\end{bmatrix} 
$$

(1)

where the inverse of the Jacobian matrix $J$ of the system is [12]:

$$
J^{-1} = \begin{bmatrix}
-H\left(C_xS_xd_{i1} - S_xd_{i1} + C_yC_{yi}d_{i1}\right) & -(hS_y + HS_yC_y)d_{i1} - (hC_y - HS_yS_y)d_{i1} \\
\frac{r(C_id_{i1} - S_id_{i1})}{r(C_id_{i2} - S_id_{i2})} & \frac{r(C_id_{i1} - S_id_{i1})}{r(C_id_{i2} - S_id_{i2})} \\
-H\left(C_xS_xd_{i2} - S_xd_{i2} + C_yC_{yi}d_{i2}\right) & (hS_y + HS_yC_y)d_{i2} + (hC_y + HS_yS_y)d_{i2} \\
\frac{r(C_id_{i2} - S_id_{i2})}{r(C_id_{i2} - S_id_{i2})} & \frac{r(C_id_{i2} - S_id_{i2})}{r(C_id_{i2} - S_id_{i2})}
\end{bmatrix}
$$

(2)

with

$$
C_x = \cos \theta_x, \ S_x = \sin \theta_x, \ C_y = \cos \theta_y, \ S_y = \sin \theta_y
$$

$$
d_{i1} = x_{Ci} - x_{Pi}, \ d_{i2} = y_{Ci} - y_{Pi}, \ d_{i3} = z_{Ci} - z_{Pi} \quad i = 1, 2
$$

(3)
To control the position of the balancing table, one of the simplest and effective methods is to build a control system based on the kinematic model of the system. Principle of controlling the balancing table which is based on its kinematic model is presented by the following equation [11]:

\[ \dot{q}_d = J^{-1} \cdot K_p \cdot dX \]  

(4)

where

\[ \dot{q}_d = \begin{bmatrix} \dot{\theta}_{1d} \\ \dot{\theta}_{2d} \end{bmatrix}^T \]

is the desired velocity vector of the two active joints;

\[ K_p \]

is a \([2\times2]\) constant positive definition matrix which mainly acts as the gain of the controller;

\[ dX = \begin{bmatrix} \theta_{1d} - \theta_x, \theta_{2d} - \theta_y \end{bmatrix}^T \]

is the error vector in orientation of the balancing table (differences between the current rotation angles of the moving table with the reference angles at the equilibrium position of the table in the global frame).

The control diagram is shown in Fig. 2. The rotation angles of the balancing table \([\theta_x, \theta_y]\) are controlled by two actuators installed at the active joints of the two parallel legs. These angles are measured by using an IMU (Inertial Measure Unit) which is mount on the moving table near the reference point O. The controller get the error in orientation and compute the desired control signals to drive the two motors (which are set in velocity control mode).

Note that he angle values \([\theta_{1d}, \theta_{2d}]\) must belong to the feasible workspace of the balancing table [12]. The geometric parameters of the balancing table in our case are selected as \(L = 0.33\) m; \(h = 0.28\) m; \(H = 0.72\) m; \(d = 0.3\) m; \(r = 0.115\) m; \(W = 0.82\) m; \(D = 0.31\) m. The working space of the system is computed: \([-10^\circ \leq \theta_x \leq 10^\circ, 25.5^\circ \leq \theta_y \leq 25.5^\circ]\). The gain matrix is selected as: \[ K_p = \text{diag}([10, 10]) \], the initial condition of the table is: \([\theta_{10}, \theta_{20}] = [0^\circ, 0^\circ]\). Fig. 3 shows the control scheme of the balancing table in Matlab.
Simulink, where we have developed a block to compute the direct kinematic model of the system using an algorithm based on Newton’s iterative method.

![Fig. 3. Simulation in Matlab Simulink](image)

We run a simulation case where the desired rotation angles are chosen as \([\theta_{xd}, \theta_{yd}] = [10^\circ, 0^\circ]\). After a time interval of 0.6s, the system reaches its steady state (Fig. 4).

![Fig. 4. Orientation errors of the balancing table](image)

In the real prototype of the 2-DOF balancing table, we used two AC Servo systems (HC-KFS43BG1) with two harmonic gears which have the transmission ratio of 1:160. To control the balancing table, we used the NI MyRio1900 as the center controller. Two IMUs 9DOF are used to measure the orientation of the moving table and the vehicle floor. The hardware connection diagram is shown in Fig. 5.
The control signals $U_1$ and $U_2$ (inputs to the AC servo drivers MR-J2S) are used to control the two AC servo systems. The NI MyRio 1900 is connected to PC via wifi so that we can collect all the data during the experiments.

The control scheme (Fig. 2) is implemented in MyMyrio using LabView Realtime module. In auto-balancing mode (mounted on a moving vehicle floor) the reference angle values are set at $[\theta_x, \theta_y] = [0^\circ, 0^\circ]$. In the case of manual control (used for testing and evaluating the system's response), the angle values $[\theta_x, \theta_y]$ are set according to the desired values in the interface control program on the user computer that connected to MyRio via wifi (Fig. 8). The control algorithm is shown in Fig. 7.
3. Experiment results

In static testing, we initialize the moving table at its equilibrium position $[\theta_{x0}, \theta_{y0}] = [0, 0]$. Then we set the angle values $[\theta_{xd}, \theta_{yd}] = [0, 5^\circ]$. The static test result (Fig. 10) shows the response time of the controller to be satisfactory, the time for quick auto-balancing is about 3 seconds.
This result is quite large compared to the simulation results in Matlab Simulink due to the low power of the motors, and because the gearbox has a large gear ratio which reduces the system response.

When testing on moving vehicles, we collected the orientation of the car floor ($\theta_{x_{\text{ref}}}$, $\theta_{y_{\text{ref}}}$) to compare with the orientation of the balancing table in order to evaluate the system ability in automatically balancing. The balancing table is mounted on a small truck which is running at a stable speed of 10 km/h. The test results are shown in Fig. 10.

The graphs show the rotation angles of the floor $\theta_{x_{\text{max}}} \approx \theta_{y_{\text{max}}} \approx 10^\circ$, the rotation angles of the balancing table are small around the equilibrium position ($\theta_{x_{\text{el}}} = \theta_{y_{\text{el}}} = 0^\circ$). Thus, the system is capable of automatically maintaining its balance on moving vehicles, reducing fluctuations due to the impacts of the road surface.

Fig. 9. Static test results

Fig. 10. Test results on vehicles at speeds of 10 km/h
However, the test results on the car are still not really good due to some reasons. Firstly, the floor vibration causes great noise to the sensors. Secondly, the actuator responses are not fast enough compared to the floor vibration frequency.

4. Conclusion

Through simulation results and practical tests, the kinematic based control algorithm is capable of keeping the table being stabilized in the horizontal plane. Although there is still a considerable amount of vibration around the reference pose, it did help to reduce the magnitudes of the table rotation angles to much smaller values which are quite good in reality.

To have a better system response, there are some issues need to be addressed carefully. Firstly, we can increase the actuator output frequency in order to react faster with the changes in angles of the vehicle floor. Secondly, we need to deal with the vibration of the vehicle floor during its operation. High frequency vibration will produce high noise in getting the acceleration data from the sensors thus will greatly affects the IMU processing. In future works, we will investigate on the dynamic properties of the system and develop solutions to increase its performance.

References


ĐIỀU KHIEN DƯA TRÊN MÔ HÌNH ĐỘNG HỌC
CHO MỘT BÀN THẲNG BẰNG 2-DOF CÓ CẤU TRÚC SONG SONG 1U-2RSS

Tóm tắt: Bài báo trình bày về bài toán thiết kế hệ thống điều khiển dựa trên mô hình động học cho một bàn thăng bằng hai bậc tự do (2-DOF) có cấu trúc song song dạng 1U-2RSS. Hệ thống được thiết kế để mang được tải trọng lớn (lên tới 100 kg) và có khả năng giữ ổn định góc quay đối với mặt phẳng ngang khi được đặt trên mặt sàn của một phương tiện di động. Kết quả mô phỏng trên phần mềm cũng như thử nghiệm trong thực tế cho thấy bộ điều khiển có thể duy trì tốt góc quay của bàn thăng bằng xung quanh vị trí ổn định của nó đối với mặt phẳng ngang.

Từ khóa: Bàn thăng bằng; kết cấu song song.

Received: 25/02/2019; Revised: 26/5/2019; Accepted for publication: 22/5/2019