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Design, Control and Planning for a Crustal Movement Simulation System

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***Abstract*—Crustal movement simulation takes the very essential effect in the research on water cycle and related land surface processes. In this paper, a crustal movement simulation system (CMSS) is presented. The system enables researchers investigate the effects of crustal movement on rivers and lakes in the laboratory environment. The CMSS proposed consists of twelve sets of parallel mechanism supported by four serial chains with three degree of freedoms (DOFs). The kinematics analysis of the parallel mechanism with four serial chains is provided. To solve the coplanar problem of four screws, a control method based on linear interpolation with parabola transition is introduced. Surface fitting algorithm based on geometric relations is used to simulate the land surface. Experiment results demonstrate the effectiveness of the system and the methods proposed.**

I. Introduction

THE crustal movement plays an important role on the development and evolution of rivers and lakes. It will change the water cycle process. Therefore, it is very critical to investigate the effect of crustal movement on the water cycle and related land surface processes (WCLSP) in the geographic science. In addition, it also has an important theoretical and practical meaning for the global sustainable development and the protection of human ecological environment [1-5].

In general, there are two major methods used to explore the effect of crustal movement on the WCLSP: field observation and indoor simulation [6]. One can discover scientific problems, and collect basic data of landform changes during field observation. But this process will take a long time due to the complexity and uncertainty of nature. This approach restricts the efficiency of research. Indoor simulation is an effective complement for filed observation. Indoor simulation consists of computer numerical and physical model simulation. Computer numerical simulation is often made in ideal conditions without considering the real field characteristics. It cannot reflect the real change of crustal movement. Therefore, constructing a scaled physical model for simulating the process of crustal movement is very necessary [7-8].

The crustal movement simulation system (CMSS) used to study the WCLSP is relatively rare currently. The Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences developed a set of crustal lifting device in 1971. The device contains two moving plates, and can just simulate simple tectonic deformations [1]. In 1982, S. A. Schumm designed a very simple crustal lifting device, which is driven by two hydraulic jacks manually [9]. Yangtze University also build a set of CMSS with four moving plates in 1996 [10]. The device has not the ability of simulating domal uplift and sag down. Although some work has been done on the CMSS, these systems are often operated manually or semi-automatically, and not enough moving plates to simulate complex tectonic movement.

Based on the research works mentioned above, we developed a novel CMSS, which consists of twelve moving plates. Each moving plate is driven by a parallel mechanism with three degrees of freedom (DOF). The system can simulate complex tectonic movement through motion combination of plates. It provides a platform, with high precision and large loads, for the research of evolution of rivers and lakes.

This paper is organized as follows. Section II describes the mechanical design of the CMSS. Kinematics analysis of single parallel mechanism is presented in section III. Section IV introduces the control design, including coordinated motion control algorithm and trajectory planning method. In section V, several experiments are shown. Finally, section VI gives a conclusion for our work.

II. Mechanical Design

Mechanical design is the basis to CMSS. The current crustal movement simulation devices were often operated manually or semi-automatically, and failed to simulate complicated crustal deformations due to the plate limitation. In this research, we developed a novel CMSS with reference to the existing crustal movement simulation equipment and user's new needs.

A. System Requirements

In order to complete crustal movement experiments perfectly, several requirements must be satisfied in the design of the CMSS [11]: 1) The ability of simulating complicated tectonic deformations; 2) High positioning accuracy: better than 0.04mm; 3) The ability of operating at a lower speed: about 0.5mm/h to 1mm/h; 4) To be able to return to the reference point rapidly after completion of the simulation tasks: from 180mm/h to 216mm/h; 5) The ability of withstanding heavy loads up to eight tons for each moving plate.

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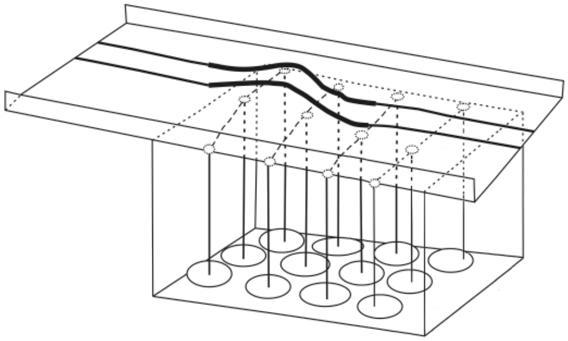

Fig. 1 Schematic illustration of the CMSS

B. Principle of the CMSS

The CMSS is designed to mainly simulate the effects of crustal movement on development and evolution of rivers and lakes. In China, most of lakes are ellipse-shaped. Taking into account the requirements mentioned above and consulting the existing mechanical designs, and related real field conditions, we believe that the entire simulation system should have at least twelve relatively independent squared moving plates to form a 4x3 array, as shown in Fig. 1. This type of system configuration can ensure that the CMSS has the ability of simulating complicated crustal movement. A large special waterproof rubber, about 4mm thick, covers above the twelve plates to form the crustal surface. It can form a variety of landforms through different combinations of position and attitude of twelve plates.

C. Mechanical Design for Parallel Mechanism

Considering the system loading requirement, each plate, in our design, is driven by a parallel mechanism. The CMSS just needs to simulate the vertical crustal movement. The plate does not need to move horizontally. Therefore, each parallel mechanism simply needs three-DOF (one translation and two rotations). Three-DOF can meet the demands for tectonic deformation, and simplify the mechanical structure. To further improve the loading capacity, each parallel mechanism is supported by four serial chains, as shown in Fig. 2. This type of mechanism takes one more serial chain than its required DOF to improve system safety and reduces the expense of each chain, although the design will make system control more difficult. For simplicity of design, the four screws are distributed symmetrically. The parameters of parallel mechanism are specified in Table I.

D. Motion Unit

In most cases, crustal movement is slower in nature, but it has an obvious accumulative effect. Therefore, the CMSS must have the ability of running for a long time at a lower speed. Additionally, it also should be able to reset to the reference position and orientation at a higher speed relatively to the working speed for the continuing experiments. In order to realize the requirement of both higher and lower speed, each motion unit is equipped with a 4Nm step motor connected to a three-order planetary reducer with a total reduction ration of 160 in this plan. Large screw nut with gear teeth, the key transmission part, will translate the rotary motion into linear motion. And this type of motion mechanism will also further reduce the speed of vertical screw through combination of gears. The slow and high motion of vertical screw is implemented by this manner.

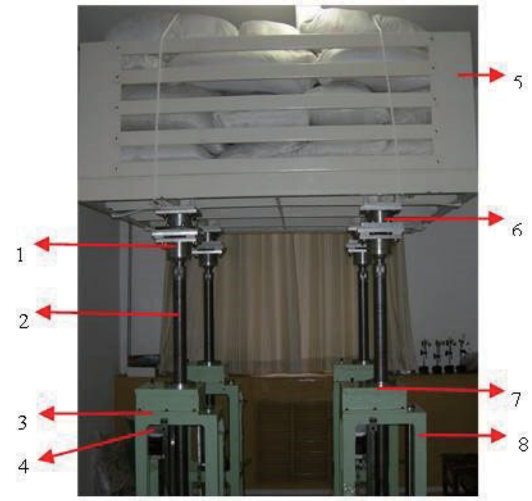

Fig. 2 Parallel mechanism for each moving plate (1 – spherical component, 2 – vertical screw, 3 – planetary reducer, 4 – step motor, 5 – top moving plate, 6 – two-dimensional translational component, 7 – screw nut with gear teeth box, 8 – base)

TABLE I
PARAMETERS OF PARALLEL MECHANISM

Name	Value
Size of base and moving plates	1.8 X 1.8 m
Distance between adjacent screw	1000mm
Motion range of screw	-400 ~ 400mm
Minimum velocity	0.5 ~ 1mm/h
Maximum velocity	180 ~ 216mm/h
Maximum load capability	8 ton

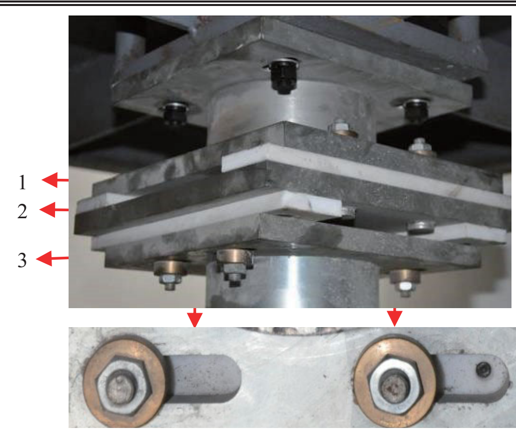

Fig. 3 Two-dimensional translational component with small amplitude (1 – the upper connection plate, 2 – the moving connection plate, 3 – the bottom connection plate)

E. Safety Considerations

The vertical screw, the terminal execution component of each serial chain, can only move vertically. Consequently, damage may be produced for the vertical screw, the base or other components if the top moving plate is directly connected to the vertical screw. A two-dimensional translational adaptive component with small amplitude is introduced to avoid damage to the device, as shown in Fig. 3. The component is a passive joint, which consists of three parts: the upper, the moving and the bottom connection plate respectively. The upper connection plate is fixed to the top plate. And the bottom connection plate is linked to the spherical component. The moving connection plate is jointed to the upper and bottom connection plate using screws, but not fixed. It can move relatively to the upper and bottom connection plate. Through this type of design, the position and orientation of the top moving plate can be slightly adjusted to compensate the movement of four vertical screws.

III. Kinematics Analysis for Parallel Mechanism

Kinematics analysis consists of two main problems: inverse kinematics and forward kinematics.

A. Geometric Description

Fig. 4 demonstrates the parallel mechanism's simplified architecture. Two coordinate systems are defined to describe the relative position and orientation of the moving plate with respect to the base plate.

A base coordinate frame, which is denoted as frame $\{B\}$, is attached to the base plate of the parallel mechanism. Points b_1, b_2, b_3, b_4 present the contact points between screw and the base plate. The origin O_B is located in the geometric center of the base plate. x_B-axis is perpendicular to vector $\overrightarrow{b_1b_3}$. y_B-axis is perpendicular to vector $\overrightarrow{b_1b_2}$. z_B-axis is perpendicular to base plate, pointing vertically upwards.

For convenience, the moving coordinate frame, which is denoted as frame $\{A\}$, is set to be coincident with the frame $\{B\}$ at the reference configuration. Points a_1, a_2, a_3, a_4 denote the contact points between screw and the moving plate. The origin O_A is positioned in the geometric center of the moving plate. x_A, y_A, z_A-axis is parallel to x_B, y_B, z_B-axis respectively, and having the same direction.

The four screws can only move vertically. The 2D translational components enable the moving plate to adjust its configuration adaptively to accommodate a variety of combinations of positions of screws. The geometric center of the moving plate will make a little horizontal change during movement. Here, for simplicity of analysis, we assume that the geometric center of the moving plate does not make any movement in the horizontal direction, that is to say, it simply moves vertically. Therefore, in the control process, we just need to consider the coplanar problem of four screws. Additionally, we also suppose that the positions of four screws are coplanar.

In Fig. 4, l presents the distance between adjacent screws; L denotes the length of side of the moving and the base plate. $h_i(i=1,2,3,4)$ denotes the position (or length) of the screws.

The contact points are written as

$$b_1 = \begin{bmatrix} l/2 \\ l/2 \\ 0 \end{bmatrix}, b_2 = \begin{bmatrix} -l/2 \\ l/2 \\ 0 \end{bmatrix}, b_3 = \begin{bmatrix} l/2 \\ -l/2 \\ 0 \end{bmatrix}, b_4 = \begin{bmatrix} -l/2 \\ -l/2 \\ 0 \end{bmatrix} \quad (1)$$

$$a_1 = \begin{bmatrix} l/2 \\ l/2 \\ h_1 \end{bmatrix}, a_2 = \begin{bmatrix} -l/2 \\ l/2 \\ h_2 \end{bmatrix}, a_3 = \begin{bmatrix} l/2 \\ -l/2 \\ h_3 \end{bmatrix}, a_4 = \begin{bmatrix} -l/2 \\ -l/2 \\ h_4 \end{bmatrix} \quad (2)$$

We can simply get the approximate solutions of kinematics, due to the special structure of parallel mechanism.

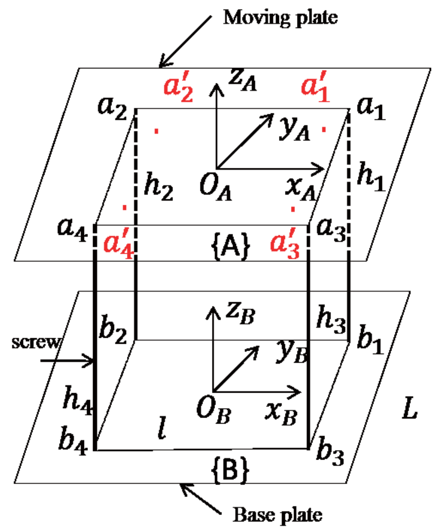

Fig. 4 Simplified architecture for parallel mechanism

B. Inverse Kinematics Analysis

An inverse kinematics problem is to solve the screw lengths, given the configuration of the moving plate. Let the configuration of the moving plate be (p_z, α, β). p_z presents the z-part of the coordinate of the origin O_A with respect to frame $\{B\}$. α, β denote the Euler angle. The rotation transformation is shown in Fig. 5.

The transformation matrix between frame $\{A\}$ and $\{B\}$ is

$$ {}^B_AT = \mathrm{Trans}(0,0,p_z)\mathrm{Rot}(x_B,\alpha)\mathrm{Rot}(y_{C,}\beta) = \begin{bmatrix} c\beta & 0 & s\beta & 0 \\ s\alpha s\beta & c\alpha & -s\alpha c\beta & 0 \\ -c\alpha s\beta & s\alpha & c\alpha c\beta & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

where $c\alpha = \cos(\alpha)$, $s\alpha = \sin(\alpha)$

In Fig. 4, points a_1', a_2', a_3', a_4' are the corresponding points of points b_1, b_2, b_3, b_4 after undergoing coordinate transformation. Define $a_i' = [x_i \quad y_i \quad z_i]^T, i = 1,2,3,4$ with respect to frame $\{B\}$.

$$\begin{bmatrix} a_i' \\ 1 \end{bmatrix} = {}^B_AT \begin{bmatrix} b_i \\ 1 \end{bmatrix} \quad (4)$$

Points a_1', a_2', a_3', a_4' are coplanar. From any three points of these four points, we can get the plane equation with respect to frame $\{B\}$.

$$AX + BY + CZ + D = 0 \quad (5)$$

where

$$A = \det\left(\begin{bmatrix} y_2 - y_1 & z_2 - z_1 \\ y_3 - y_1 & z_3 - z_1 \end{bmatrix}\right)$$
$$B = -\det\left(\begin{bmatrix} x_2 - x_1 & z_2 - z_1 \\ x_3 - x_1 & z_3 - z_1 \end{bmatrix}\right)$$
$$C = \det\left(\begin{bmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y_1 \end{bmatrix}\right)$$
$$D = -Ax_1 - By_1 - Cz_1$$

From (5), we can get the Z-axis coordinates (the length of the screws) of the points a_1, a_2, a_3, a_4 with respect to frame

{B}.

$$h_i = a_i^z = -\frac{Aa_i^x + Ba_i^y + D}{C}, i = 1,2,3,4 \quad (6)$$

where a_i^x, a_i^y, a_i^z denotes the x、y、z value of a_i respectively.

C. Forward Kinematics Analysis

Forward kinematics is to find the configuration of the moving plate, given the screw lengths. For simplifying the analysis, we assume that points a_1, a_2, a_3, a_4 are located in a same plane. Hence, using the plane geometric relations, we can get

$$p_z = \frac{h_2 + h_3}{2} \text{ or } p_z = \frac{h_1 + h_4}{2} \quad (7)$$

The plane equation with respect to frame {B} can be derived as

$$A_1 X + B_1 Y + C_1 Z + D_1 = 0 \quad (8)$$

where

$$A_1 = \det\left(\begin{bmatrix} a_2^y - a_1^y & a_2^z - a_1^z \\ a_3^y - a_1^y & a_3^z - a_1^z \end{bmatrix}\right)$$

$$B_1 = -\det\left(\begin{bmatrix} a_2^x - a_1^x & a_2^z - a_1^z \\ a_3^x - a_1^x & a_3^z - a_1^z \end{bmatrix}\right)$$

$$C_1 = \det\left(\begin{bmatrix} a_2^x - a_1^x & a_2^y - a_1^y \\ a_3^x - a_1^x & a_3^y - a_1^y \end{bmatrix}\right)$$

$$D_1 = -A_1 a_1^x - B_1 a_1^y - C_1 a_1^z$$

The solving process is similar to that of (5).

Omitting the translational movement along vertical direction, we just consider the rotation transformation, as shown in Fig. 5. Frame {B} is the base frame. Frame {C} is obtained after frame {B} rotates angle α around $O_B x_B$ axis. Frame {A} is derived after frame {C} rotates angel β around $O_C y_C$ axis.

Firstly, we solve angle β. Angle β is equal to the angle between vector $\overrightarrow{O_B x_B}$ and the plane that cross origin O_B and perpendicular to $\overrightarrow{O_A z_A}$. $\overrightarrow{O_B x_B} = \{1, 0, 0\}$, Therefore

$$\sin(\beta) = \frac{|A_1|}{\sqrt{A_1^2 + B_1^2 + C_1^2}} \quad (9)$$

$$\beta \begin{cases} < 0 & 90^\circ \le \theta_y < 180^\circ \\ \ge 0 & 0 \le \theta_y < 90^\circ \end{cases} \quad (10)$$

where θ_y denotes angle between vector $\overrightarrow{O_B x_B}$ and $\overrightarrow{O_A z_A}$.

In order to solve angel α, the plane (8) must first rotate angle $-\beta$ around $O_C y_C$ axis. Then, the coordinate system located in the plane after transformation will be coincident with the frame {C}. Therefore, angle α is equal to the angle between vector $\overrightarrow{O_B y_B}$ and the plane that cross origin O_C and perpendicular to $\overrightarrow{O_C z_C}$.

The normal vector of the plane {8} is given as $\overrightarrow{O_A z_A} = \{A_1, B_1, C_1\}$. The transformation matrix between frame {A} and {C} is written as

$${}_C^A T = Rot(y_C, -\beta) = \begin{bmatrix} c\beta & 0 & -s\beta & 0 \\ 0 & 1 & 0 & 0 \\ s\beta & 0 & c\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (11)$$

Define $\overrightarrow{O_C z_C} = \{A_2, B_2, C_2\}$,

$$[A_2 \quad B_2 \quad C_2 \quad 1]^T = {}_C^A T [A_1 \quad B_1 \quad C_1 \quad 1]^T \quad (12)$$

From the geometric relations, we can easily get that the angel α can also be written as

$$\alpha = \theta_x - 90 \quad (13)$$

where θ_x is the angle between vector $\overrightarrow{O_B y_B}$ and $\overrightarrow{O_C z_C}$. $\overrightarrow{O_B y_B} = \{0, 1, 0\}$.

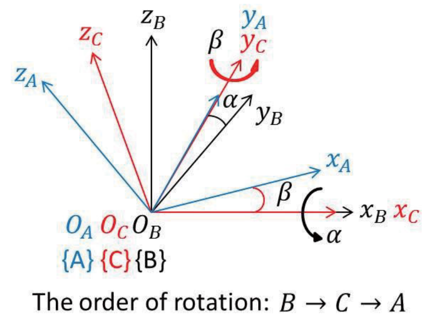

Fig. 5 Rotation transformation

IV. Control System Design

A. Coordinated Control for Parallel Mechanism

From the perspective of safety, the vertexes of four screws must be coplanar during deformation. The coplanar angle is described as

$$\theta_{coplane} = \left| 90 - \arccos\left(\frac{(\overrightarrow{a_2 a_4} \times \overrightarrow{a_2 a_1}) \cdot \overrightarrow{a_4 a_3}}{|\overrightarrow{a_2 a_4} \times \overrightarrow{a_2 a_1}| \cdot |\overrightarrow{a_4 a_3}|}\right) \right| \quad (14)$$

where

$$\begin{aligned} \overrightarrow{a_2 a_4} &= [0 \quad -l \quad h_4 - h_2]^T \\ \overrightarrow{a_2 a_1} &= [l \quad 0 \quad h_1 - h_2]^T \\ \overrightarrow{a_4 a_3} &= [l \quad 0 \quad h_3 - h_4]^T \end{aligned} \quad (15)$$

We assume that the four screws are coplanar when

$$\theta_{coplane} \le 0.05^\circ \quad (16)$$

In addition to planning the motion trajectory of the moving plates, we also have to plan the motion trajectory of screws when the moving plate moves from one configuration to another configuration. In order to ensure that the four screws are coplanar, the coordinated control of four screws (four joints) must meet the following conditions: 1) to be launched at the same time; 2) to enter the stage of steady speed simultaneously; 3) to enter the stage of reducing speed at the same time; 4) to be stopped simultaneously; 5) to have same sampling period, control period, and motion time. The speed curve is shown in Fig. 6.

In our trajectory planning for joints, we adopt the linear interpolation with parabola transition. Fig.7 presents the planning flow. The four joints have the same transition time T_b through adjusting the acceleration.

To improve system accuracy, we also must adjust the motion speed slightly according to the current and targeted positions within every sampling and control period.

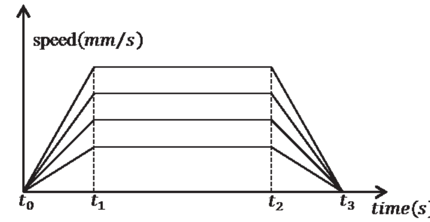

Fig. 6 Coordinated control illustration

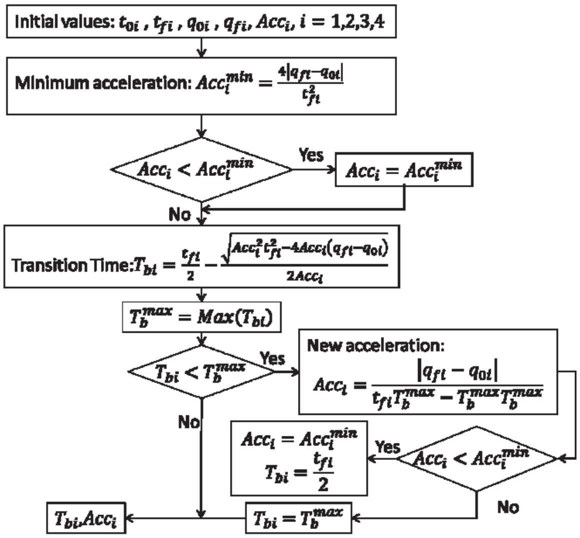

Fig. 7 Flow chart of linear interpolation with parabola transition

B. *Planning for Crustal Deformation*

The CMSS is used to investigate the effects of crustal movement on evolution of rivers and lakes. The main crustal movement consists of crustal rise and fall, tilting, fault block, anticline folding, syncline folding, circular vault, elliptic vault, sag, graben, horst, and so on.

Landform can be constructed through adjusting positions and orientations of twelve moving plates. Positions and orientations of twelve moving plates have many combinations, so there are a variety of landforms. Taking syncline folding with horizontal axis for an example, we introduce how to obtain positions and orientations of the moving plates.

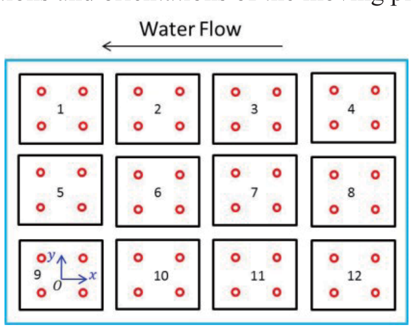

Fig. 8 Layout for moving plates

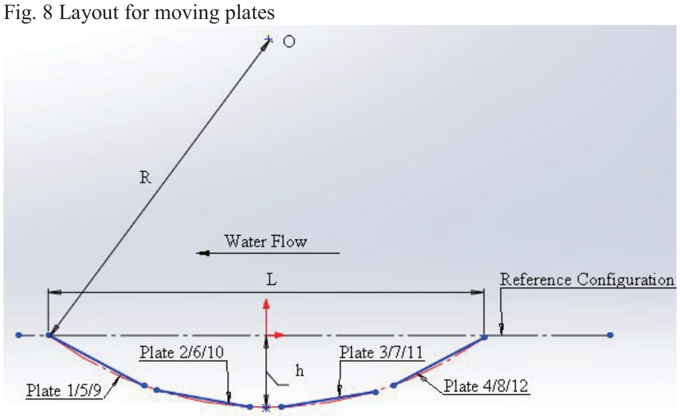

Fig. 9 Schematic illustration for syncline folding with horizontal axis

The layout for moving plates is shown in Fig. 8. Fig. 9 shows the schematics illustration for syncline folding with horizontal axis. Looking from the profile view along water flow, the upper surface of the twelve moving plates constructs an arc-shaped surface. Each plate simply moves along vertical direction and rotates around its y-axis. The plate 1, 5 and 9 has the same configuration. Other plates have the similar features. Using geometric relations, we can easily get the position and orientation for each parallel mechanism. Given the height of arc h and the length of chord L, The radius R of the arc can be denote as

$$R = \frac{4h^2+L^2}{8h} \tag{17}$$

Therefore, we can obtain the height of the side of each plate, and then get the end configuration (p_z, α, β) of each plate. And the length of screws can be obtained through inverse kinematics.

Other landform construction is similar to that of syncline folding with horizontal axis.

V. Experiments

To evaluate the performance of the system, the simplified kinematics modeling, and the motion planning methods, extensive experiments have been carried out.

A. *Verification for simplified kinematics modeling*

Due to the special structure of parallel mechanism, we cannot get the exact kinematics modeling. In section III, we simply get the approximate solutions of forward and inverse kinematics. For evaluate the effectiveness of the solutions, we developed a test program in Matlab. The verification process is as follows: 1) to calculate the length of screws, given the configuration of the moving plate, through inverse kinematic model; 2) to solve the configuration of the moving plate using the lengths that were obtained from step one, through forward kinematics model; 3) to compare the two configurations. We selected 8 sets of different configurations. The comparison results are shown in Table II. The maximum value for α, β is ± 8 degree, because of the mechanical limitation.

From Table II, we can see that p_z and β are totally identical. Angle α makes a little change, and the smaller the initial angle is, the smaller the change between the initial and resulted angle is. The error is within our requirements.

B. *Experiments for Crustal Movement*

Similar to section IV-B, we also take syncline folding with horizontal axis for an example to introduce the experiment. It was assumed that the twelve plates were located in the reference configuration before deformation. 3D sketch for syncline folding with horizontal axis is presented in Fig. 10. The aspect ratio of the x-, y-, and z-axis is not the same in order to better display the 3D surface in Fig. 10. The real crustal deformation is given in Fig. 11. The two figures have the same shape. The surface of the twelve plates is symmetrical about X- and Y-direction (see Fig.11). We can just consider the movement of the plate 1 and 2. From the section IV-B, we know that plate 1 and 2 only have a rotation movement around its y-axis. Therefore, the movement of axis 1-2, 1-1, 2-2, and 2-1 (see Fig. 11) can represent the movement of all

TABLE II
COMPARISONS FOR RESULTS OF KINEMATICS ANALYSIS

No.	Initial configuration			Length of screws			Result configuration			
	p_z	α	β	h_1	h_2	h_3	h_4	p_z	α	β
1	0	8	8	-0.691	141.231	-141.234	0.691	0	7.922	8.000
2	0	-8	-8	0.691	-141.231	141.231	-0.691	0	-7.922	-8.000
3	0	8	-8	141.231	-0.691	0.691	-141.231	0	7.922	-8.000
4	0	-8	8	-141.231	0.691	-0.691	141.231	0	-7.922	8.000
5	50	1	2	41.265	76.191	23.809	58.736	50	0.999	2.000
6	100	2	4	82.476	152.445	47.555	117.524	100	1.995	4.000
7	200	3	3	199.9640	252.444	147.556	200.036	200	2.996	3.000
8	300	4	-4	370.012	299.915	300.085	229.988	300	3.990	-4.000

Note: the units for p_z, α, β, $h_i (i = 1,2,3,4)$ are millimeter, degree, degree, and millimeter respectively.

plates. The position curve for axis 1-2, 1-1, 2-2, and 2-1 is shown in Fig 12.

Other main tectonic deformations of crustal movement are shown in Fig. 13, including anticline folding with oblique axis, big/small elliptic vault, and circular vault.

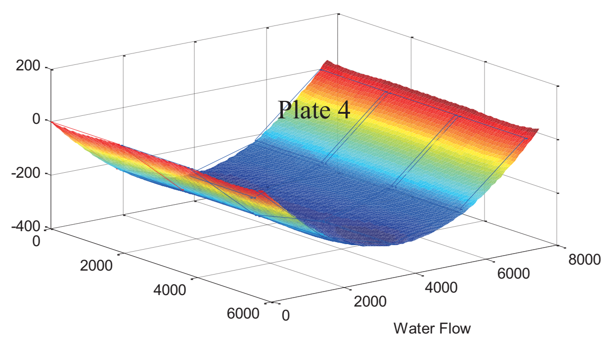

Fig. 10 3D sketch for syncline folding with horizontal axis

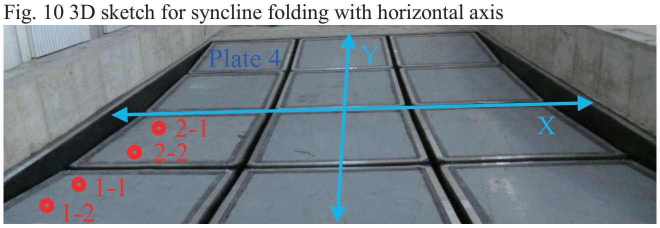

Fig. 11 Experimental result for syncline folding with horizontal axis

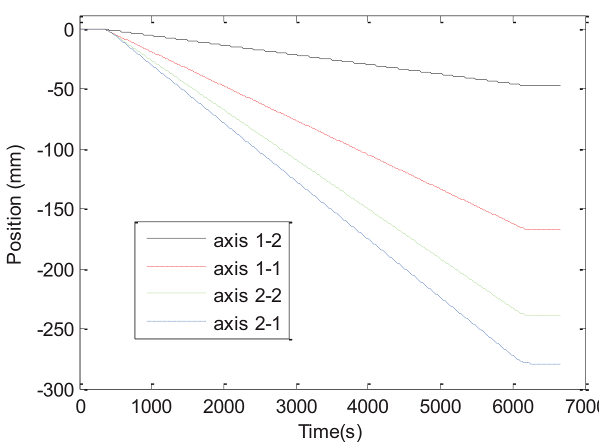

Fig. 12 Position Curve for axis 1-2, 1-1, 2-1, and 2-1

VI. CONCLUSION

In this paper, we developed a novel platform used to simulate the crustal movement for the WCLSP. This system helps geographic researchers better understand the effects of crustal movement on the development and evolution of rivers and lakes. Further work will concentrate on the study of terrain construction methods.

Fig. 13 Crustal deformations (1- anticline folding with oblique axis, 2-big elliptic vault, 3-circular vault, 4-small elliptic vault)

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