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Platform-Level Design for a Crustal Movement Simulation System*

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***Abstract* - It's very important to investigate the effect of crustal movement on water cycle and related land surface processes in the laboratory environment for geographic researchers, especially the influence of tectonic deformations on the basin, the river course and the estuary. In this paper, a crustal movement simulation system (CMSS) is proposed, including the mechanical design and related control system of the CMSS. The CMSS is implemented with twelve sets of parallel mechanism supported by four serial chains with three degrees of freedom (DOF). Hierarchical control architecture with embedded controller is constructed, which can control the CMSS to accomplish user-defined tectonic movements automatically. Experimental results, performed on test facilities reproducing the real field conditions, are also presented.**

Index Terms - crustal movement; tectonic deformation; parallel mechanism; hierarchical control architecture.

I. INTRODUCTION

Nowadays, the effect of crustal movement on the water cycle and related land surface processes (WCLSP) has become one of the most significant research issues in the geographic science. Crustal movement has a critical impact on the evolution of the basin, the river course and the estuary, which also will cause aquifer deformation and then change the water cycle process. Therefore, it is very important to study the effect of crustal movement on the WCLSP for exploring coupling mechanism of water cycle, coupling mechanism of water cycle and land surface and evolution of river course. It's an irreplaceable important means for geosciences. 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].

General speaking, field observation and indoor simulation are the two main approaches used to explore the process of crustal movement [6]. One can discover scientific problems, and obtain first-hand data of the real landform changes by field observation. But it will take a long time due to the complexity and uncertainty of nature and spatio-temporal variability of the data. This approach restricts the process and 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 conducted in an ideal condition without considering external disturbance and real hardware's characteristics. It cannot reflect the real process of crustal movement. Therefore, it is very imperative to construct a scaled physical model for simulating the process of crustal movement. It has many advantages to use such a physical model [7-8]:

- To shorten time and space scales of the process of crustal movement.
- To enhance the depth and breadth of understanding of evolution of the WCLSP.
- To verify evolution hypothesis of the WCLSP.
- To reveal the internal micro-process of evolution of the WCLSP.
- More convenient and advanced observation methods.

The crustal movement simulation system (CMSS) used to investigate the WCLSP is less common currently. The Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences build a set of unique crustal lifting device of the world in 1971, which was composed of two moving plates and can simply simulate several simple tectonic movements [1]. In 1982, S. A. Schumm and Sunju Oucha developed a very simple crustal lifting device, which is driven by two hydraulic jacks manually [9]. Yangtze University (formerly Jianghan Petroleum University) designed a set of CMSS with four moving plates, without the ability of simulating domal uplift and sag down in 1996 [10-11]. 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 a parallel mechanism with three degrees of freedom (DOF) and its load capacity can be up to eight tons. The system can simulate complex tectonic movement (such as domal uplift, sag down, fold) through motion combination of plates. It provides a platform, with high precision and large loads, for the research of evolution of the WCLSP.

This paper is organized as follows. Section II describes the mechanical design of the CMSS according to user's requirements. Then the control system, including hardware and software design, is introduced in section III. In section IV, several experiments are shown. Finally, section V gives a conclusion for our work.

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II. MECHANICAL DESIGN

Mechanical design is one of the most significant parts for the CMSS. Although some of crustal movement simulation devices have been developed, these devices were operated manually or semi-automatically, and failed to simulate complicated crustal deformations. In this research, we designed a novel CMSS with reference to the existing crustal movement simulation equipments and user's demands.

A. Requirements for Mechanical Design

Mechanical design for the CMSS is one of the most difficult parts during system development process. In order to complete crustal movement experiments for the WCLSP perfectly, the CMSS designed must satisfy the requirements described as follows:

- To have the ability of simulating a variety of tectonic deformations, including the uplift, the decline, the incline, domal uplift, sag down, fold and so on.
- To have high precision: better than 0.04mm.
- To be capable of running for a long time at a lower speed when performing crustal movement simulation tasks: about 2mm/h to 3mm/h.
- To be able to return to the reference point rapidly after completion of the simulation tasks: from 180mm/h to 216mm/h.
- To withstand large loads up to eight tons for each parallel mechanism.
- To have enough security mechanism to avoid damage to human and machine.
- To be operated automatically.

B. Mechanical Design of the CMSS

Taking into account the requirements mentioned above for the CMSS and consulting the existing mechanical designs, we believe that the entire simulation system should have at least twelve parallel mechanisms to form a 4x3 array, as shown in Fig. 1. Each mechanism has a squared plate on the top and a large integrated thin rubber covers on the twelve mechanisms to form the crustal surface. This type of system configuration can ensure that it has the ability of simulating complicated crustal movement. We designed a three-DOF parallel mechanism supported by four serial chains for each moving plate, as shown in Fig. 2. Three-DOF (one translation and two rotations) can meet the demands for tectonic deformation, and simplify the mechanical structure. The mechanism takes one more serial chain than its required DOF to improve system safety and reduces the expense of each chain. It can also make the mechanism to bear loads up to eight tons, although the design will make system control more difficult.

Each serial chain consists of base, supporting components, motion unit, vertical screw, spherical component and two-dimensional translational component with small amplitude. The upper moving plate is able to achieve different positions and attitudes through motion of four motors, forming various tectonic deformations. Different landforms can be obtained through combination of twelve top moving plates.

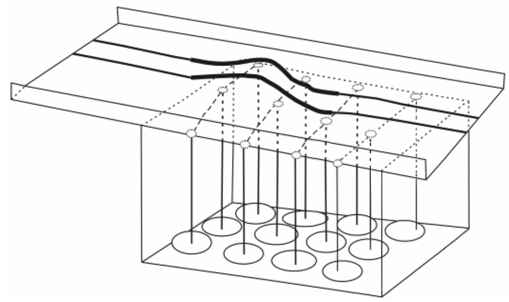

Fig. 1 Schematic illustration of the CMSS

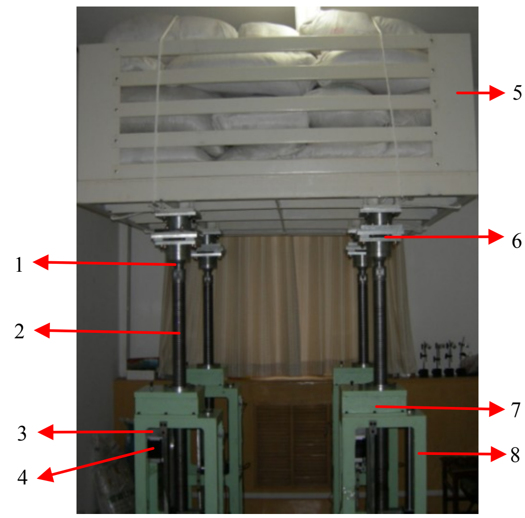

Fig. 2 Parallel mechanism for each moving plate (1 – spherical component, 2 – vertical screw, 3 – planetary reducer, 4 – step motor, 5 – top moving plate, 6 – two-dimensional translational component, 7 – screw nut with gear teeth box, 8 – base)

The effect of crustal movement on the WCLSP is slower than that of water flow, but it has an obvious accumulative effect. Therefore, the CMSS must have the ability of running for a long time at a lower speed, without the existence of delay or crawl. Additionally, it should be able to reset to the initial position and attitude 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 rotation motion of the step motor is then transmitted to the vertical screw by planetary reducer and screw nut with gear teeth. The slow and high motion of vertical screw is implemented by this manner.

The vertical screw, the terminal execution component of each serial chain, can only move in vertical direction. 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 fixed 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 attitude of the top plate can be slightly adjusted to compensate the movement of four vertical screws.

The base, located in the ground, is made of cast iron to ensure that it is capable of enduring loads up to eight tons without any deformations during motion.

In addition, in order to enhance the performance of balance of system, we also designed several supporting components, as shown in Fig. 4, which can guarantee that the vertical screw will maintain the vertical direction during the process of rising or declining.

III. Control System

A hierarchical control system was proposed for the CMSS to simplify development process and shorten development time. The control task will be reasonably compartmentalized into several subtasks assigned to different controllers through hierarchical control structure. This type of control structure can make the parallel mechanisms complete the motion control more rapidly and accurately. The entire control system for the CMSS was composed of one decision-making computer, twelve master controllers, twelve step motor controllers and one manual-control box. The manual-control box is simply used during the mechanical and electrical debugging period.

A. Architecture of Control System

Fig. 5 illustrates the structure of control system for the CMSS. The control system is divided into four layers: decision-making and supervisory layer, motion planning and coordinating layer, motion control layer and actuator layer respectively.

Decision-making computer, belonging to the decision-making and supervisory layer, is the top decision-maker for the entire control system. It determines the positions and attitudes of twelve parallel mechanisms to form different tectonic deformations. In order to fulfill the functionality, it provides a Graphical User Interface (GUI), which is an OpenGL-based three-dimensional (3D) software especially developed for the CMSS. Users can configure the relevant landforms needed to be simulated via the GUI. Then, it will analyze the user self-defined simulation task automatically, and judge whether the task is feasible or not. It will give a warning message to user if the simulation task is infeasible. Feasible simulation task will be downloaded into the master controllers located in the motion planning and coordinating layer via CAN bus. Real-time data from sensors and motors will also be displayed in the decision-making computer in the form of tables and 3D graphics. Furthermore, it will also provide additional functionalities to help user control the CMSS more effectively, such as fault warning, diagnosis and solution, and asynchronous operation

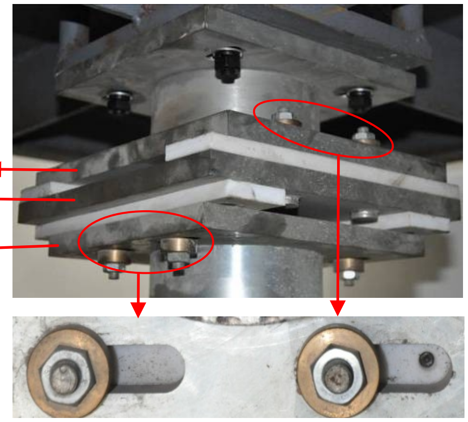

Fig. 3 Two-dimensional translational component with small amplitude (1 – the upper connection plate, 2 – the moving connection plate, 3 – the bottom connection plate)

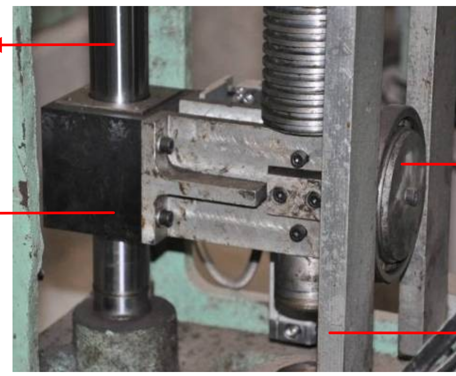

Fig. 4 Balance components (1, 4 – guiding bar, 2 – linear rolling bearing, 3 – radial ball bearing)

mode. Asynchronous operation mode is an effective complement to the coordinated control, which makes users control motor motion manually. The operation mode greatly improves the system flexibility.

In the motion planning and coordinating layer, one mater controller is responsible for the motion control of one parallel mechanism. This layer is one of the most important parts of the control system. The master controller will create motion trajectory for the corresponding parallel mechanism according to the set value of position and attitude from decision-making computer. And it will also solve the expected position and velocity of each joint by the inverse kinematics analysis of parallel mechanism. In addition, it will sample the real position and velocity of each joint. Considering the combination of the desired motion sequences and sensor information, it will send the corresponding control commands to the motion control layer.

The step motor controller, located in the motion control layer, is in charge of driving step motors to fulfill the predefined landform simulation tasks. The signals from sensors and encoders will be transmitted to the signal preprocessor for further use.

Communication, between the decision-making computer and the master controllers positioned in the control cabinets, is implemented with CAN bus via CAN communication card. And, the master controller communicates with the step-motor controller and the signal preprocessor through IIC bus.

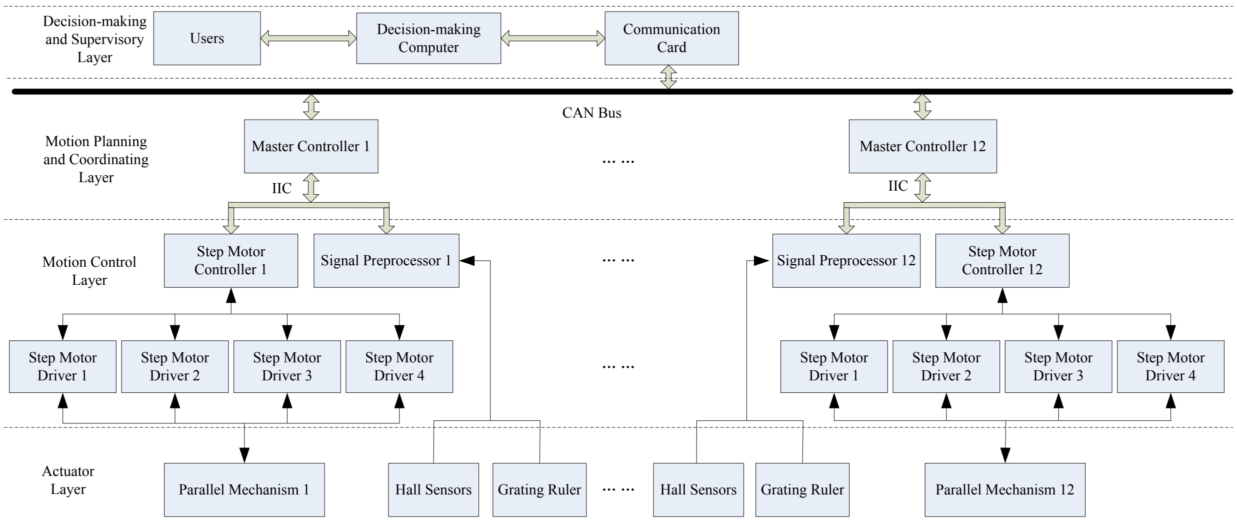

Fig. 5 Structure of control system

B. Hardware Design

Hardware system of the CMSS consists of master control module, motion control module, signal preprocessing module, communication module and sensor module. The CMSS has a requirement of high reliability not only for the mechanical structure, but also for the control system. The operation for the CMSS is a challenging job for both equipment and operators, since each parallel mechanism of the CMSS has to withstand loads up to eight tons. Security is the first consideration to the system. Therefore, the scheme of ARM combined with FPGA is provided to improve the real-time performance, safety and reliability of the system based on the above mentioned.

ARM is utilized to serve as the core component of master control module, due to its high performance and flexibility. It has abundant peripheral interface circuits, and can embed a real-time operating system.

PFGA, the kernel of motion control module, is used to produce PWM control signals to drive step motors. It may change the frequency and amplitude of PWM control signals according to the commands from master control module.

The signals from sensors are not unified and standard in voltage levels, since the system has multiple types of sensor. Therefore, the signal preprocessing module, serving as input and output interface, is provided to preprocess signals from sensors. It can transform the voltage of signals to the unified level for the convenience of use of ARM and FPGA.

The sensors used for the CMSS contain grating ruler and Hall sensor. The purpose of using grating ruler is to obtain the real-time position of vertical screw. There are three Hall sensors for each serial chain of parallel mechanism: one for determination of reference point, and the other two for protecting the mechanical system when the vertical screw approaches the upper or the bottom limited position. Sensor information is integrated properly to be used as feedback of closed-loop control of the motor, and security protection mechanism.

C. Software Implementation

The software system for the CMSS is composed of foundation and application software. The software system is divided into many modules to accomplish the simulation task of crustal movement, as shown in Fig. 6.

From the control and security point of view, the software system must have the ability of fast response, guaranteeing that it can make correct decisions in time especially when fault occurs. Hence, the embedded real-time operating system uC/OS, with a preemptive kernel, is a satisfactory solution. uC/OS is an open source software, most of which is written in highly portable ANSI C, and has the merit of reducing the occupied memory. Each module of foundation software corresponds to an identical user task that can run in parallel. This mechanism greatly improves the real-time performance of system.

The application software was developed in Qt and Visual Studio 2005 on windows, as shown in Fig. 7. It's an OpenGL-based 3D software. In Fig. 7, region 1 is the area that displays

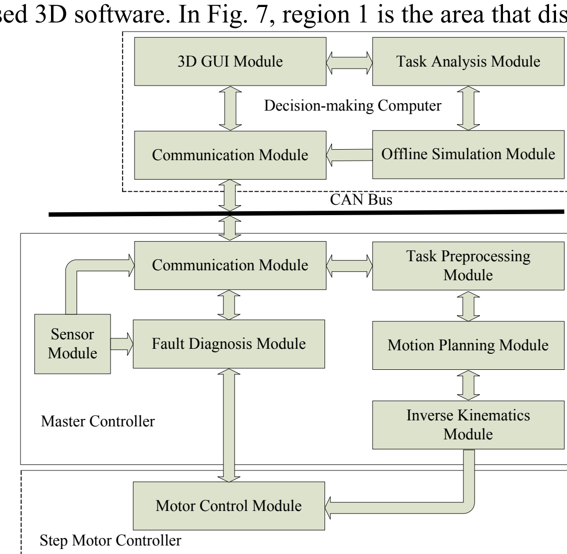

Fig. 6 Software structure of the CMSS

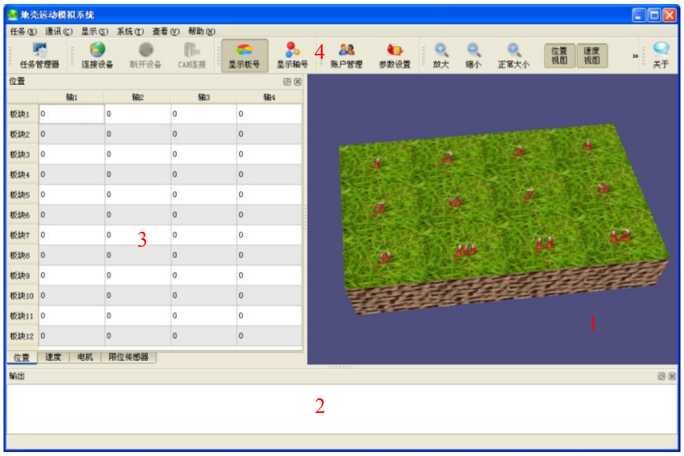

Fig. 7 3D application software

the real-time 3D landforms, in which the positions of four vertical screws for each parallel mechanism are translated into the position and pose of top moving plate via the forward kinematics analysis of parallel mechanism. Region 2 shows some of system information, such as communication status, fault and warning. And the information is also stored in the disk for further processing or checking later. Region 3 displays the real-time data of all moving plates in the form of tables, such as the position, velocity and status of motors, the status of sensors and the other system information. All control functions are implemented via region 4.

Some key modules are described as follows:

- Communication module. The decision-making computer communicates with the master controller via CAN bus based on self-defined CAN communication protocol, which provides a reliable, stable and high-speed bidirectional interaction [12].
- Task preprocessing module. This module is designed to decompose the information of simulation task into low-level motor trajectories.
- Motion planning module. This module is used to produce motion sequences for the simulation task based on user's configuration.
- Inverse kinematics module. It performs the inverse kinematics analysis of parallel mechanism.
- Fault diagnosis module. It is used to detect system faults and then give warning information and fault solutions based on fault library of the system.
- Motor control module. It outputs the PWM signals for controlling step motors.
- Sensor module. Sensor data is send to this module. It will send the processed data to other corresponding module for further processing.
- Task analysis module. The feasibility of the simulation task is verified in this module.
- 3D GUI module. It provides an interface for user to define the simulation task. And, the real-time motor data and system status are also displayed in this module.
- Offline simulation module. It performs the offline simulation to better understand the execution process of task.

IV. Experiments

To verify rationality, effectiveness and performance of the system designed, several experiments have been performed in test facilities that reproduce the conditions that the CMSS is expected to face. The parameters of parallel mechanism are specified in Table I. The experimental results are briefly described as follows.

A. *Experiment of Load and Tectonic Deformation*

The parallel mechanism is able to withstand maximum loads up to eight tons without any damage to the mechanism, as displayed in Fig. 8.

Fig. 8 also shows several main tectonic deformations of crustal movement, such as the lateral incline, the longitudinal incline and the diagonal incline.

B. *Experiment of Velocity*

The parallel mechanism has the ability of moving at the velocity of 2mm/h consistent with the minimum velocity specified in the requirements, as shown in Fig. 9. And the low-velocity motion process is smooth, without delay or crawling. The maximum velocity can reach to about 234mm/h, above the required maximum velocity, as shown in Fig. 10.

From the experiments above, we can see that the system developed is enough to perform the simulation task of crustal movement. The mechanical system is suitable for the CMSS, and control system is efficient for the CMSS.

V. Conclusion

In this paper, we developed a novel platform used to simulate the crustal movement for the WCLSP, and conducted a preliminary test for it. We introduced the mechanical design of the given system, and hierarchical control architecture was proposed to be used for control of the CMSS. Furthermore, the hardware and software system for the CMSS were also discussed. Experiments of tectonic deformation presented in this study showed the excellent performance (large load, high accuracy and low speed) of the system proposed. Further work will concentrate on the coordinated control of multi parallel mechanisms.

Acknowledgment

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TABLE I
Parameters of Parallel Mechanism

Distance between adjacent vertical screws	1000mm
Motion range of vertical screw	-400 ~ 400mm
Minimum velocity	2~ 3mm/h
Maximum velocity	180 ~ 216mm/h
Maximum load capability	8 tons

Fig. 8 Tectonic deformations (1 – left incline, 2 – right incline, 3 – forward incline, 4 – diagonal incline)

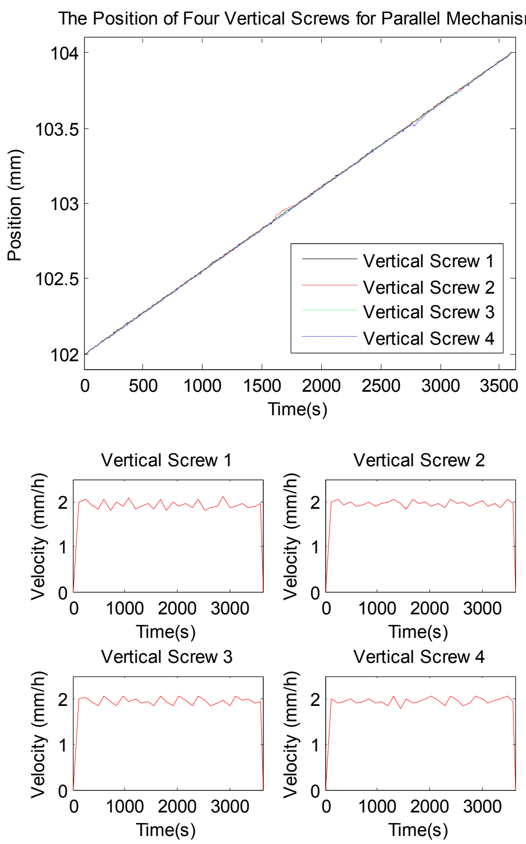

Fig. 9 Experimental result for lower-velocity motion

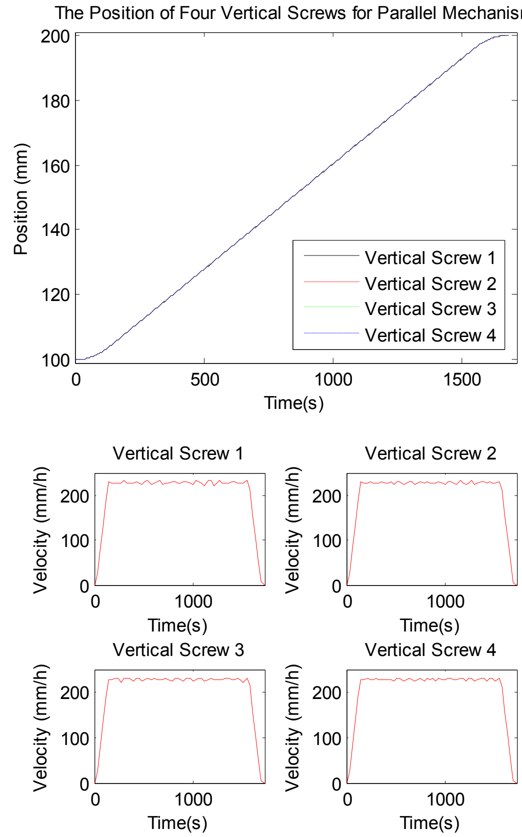

Fig. 10 Experimental result for higher-velocity motion

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