Development of a four-axis robotic manipulator for centrifuge modeling at HKUST

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ABSTRACT: The Geotechnical Centrifuge Facility at Hong Kong University of Science and Technology (HKUST) has recently acquired and commissioned a four-axis robotic manipulator for its 400-gt geotechnical centrifuge. The manipulator is designed to serve as a platform on which many computer-controlled activities such as excavation and loading can be performed.

Central components of this robot are linear and rotary driving mechanisms, a tool changer with multiple tool adapters, and a motion controller. The driving mechanisms are to control movements in the three-dimensional space as well as rotation about the vertical axis. The maximum strokes are 875, 838 and 317 mm in the x, y, and z directions respectively, and the maximum rotation angle is 270°. The load capacities are ±5 N·m torque, and ±1000 N, ±1000 N, ±5000 N forces in the x, y, z directions, respectively. Four different types of tools can be handled using the tool changer and four tool adapters installed on the main frame. Fluid pressure and electrical signals can also be transmitted to the working tool through the tool changer and adapters. The sequence of motion is controlled through a ROBotic Control System (ROBCOS). Instructions can be input either through a teaching pendant or through a keyboard manually. The robotic manipulator has been used to correct an initially tilted building using soil extraction technique in-flight. The test set-up and some results of this test at 30 g are described in this paper.

1 INTRODUCTION

The HKUST Geotechnical Centrifuge Facility has recently acquired and commissioned a four-axis robotic manipulator for its 400-gt geotechnical centrifuge. The four-axis robotic manipulator is dedicated to serve as a platform on which many computer-controlled activities (excavation, loading, CPT, and surface scanning etc.) can be performed.

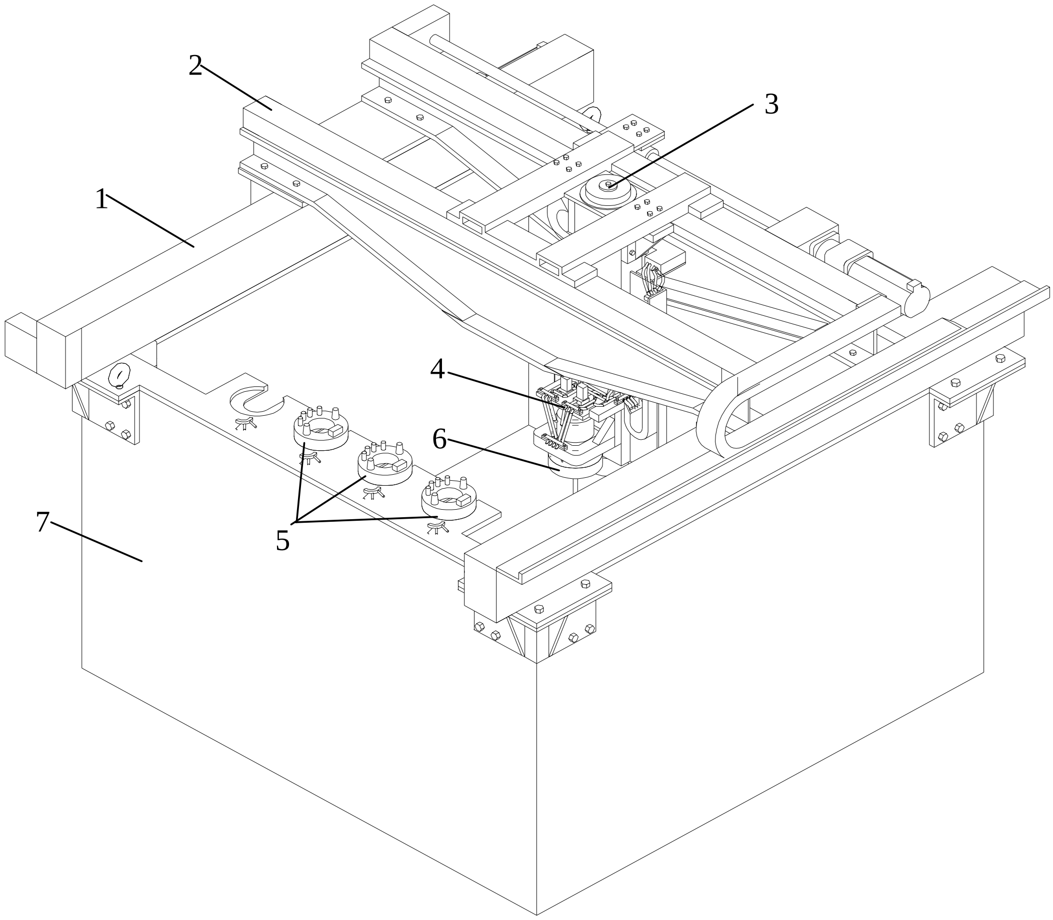
In-flight simulation of geotechnical problems in a centrifuge is by no means easy. Although researchers in many centrifuge centers have developed motor driven or fluid (hydraulic oil or compressed air) driven devices for simulating construction and loading of geotechnical structures (Almeida and Parry, 1984, Kimura et al, 1994), non-stop simulation involving several activities is still extremely difficult. The idea of a robotic manipulator is to provide a universal platform on which many different tasks involving multiple activities can be carried out continuously in flight. Derks et al. (1998) described perhaps the first robotic manipulator for use in centrifuge modeling. The robotic manipulator for the HKUST geotechnical centrifuge, which is larger, is perhaps the second of its kinds.

The design of the HKUST robotic manipulator is targeted to offer the maximum capability for simulating a variety of geotechnical problems in a user-friendly manner with minimum costs. This paper introduces the specifications, structure, control system, and man-machine interface of the robotic manipulator. Potential applications and development of "tools" for these applications are also discussed.

2 SPECIFICATIONS AND DESIGN

2.1 *Mechanical design and specifications*

Figure 1 shows the schematic view of the robot. The structure of the robotic manipulator consists of three major components, i.e., the linear and rotary driving mechanisms, a tool changer with multiple tool adapters, and the motion controller. Figure 2 shows a photograph of the robot in action at 1-g. The robotic manipulator is designed to operate while exposed to 1 – 150 g steady centripetal acceleration in the vertical (z) direction. When mounted at the end of the centrifuge arm, the robot system is exposed to a maximum wind velocity of 75 m/sec when the centrifuge is operating at maximum speed. The robot is



1. Ball screw on x-axis
2. Rail on y-axis
3. Linear driving mechanism in z-axis
4. Rotary actuator
5. Tool adopters stored in the fixture
6. Working tool adopter
7. Model container

Figure 1. A schematic diagram of the 4-axis robotic manipulator.

able to operate in the presence of small amounts of windblown sand, silt and moisture since all roller bearings, electrical enclosures and motors are sealed. Nominal ambient operating temperature is 25 ºC.

The robotic manipulator is mounted on a large model container, whose inside dimensions are 1245 mm × 1270 mm × 762 mm (Shen et al, 1998; Ng et al. 2001). The manipulator is attached to the container using ½-12 screws through holes on the model container walls. It is designed as a single unit with suitable lifting eyes to be handled by using an overhead crane.

The driving mechanisms are able to control movements in the three-dimensional space as well as rotation in the horizontal plane. The x, y, and z axes as well as the θ axis are driven by AC servomotors through motor drivers. Each of the motors has an electromagnetic brake, which can act when the power is off.

The main specifications of the 4-axis robotic manipulator are listed in Table 1. Motion control in each of the axes is via displacement-feedback (i.e. displacement control mode). At 1-g, an absolute accuracy over the entire range of travel in the x, y, and z directions is 0.3 mm. At 150 g, the accuracy is expected to be 1.0 mm. The manipulator incorporates brakes to maintain a fixed position when it is not being commanded to change its location. The load capacity has been tested to the full values at 1-g. At high g field, a compressive load capacity in the z-direction larger than 5000 N may be allowed.

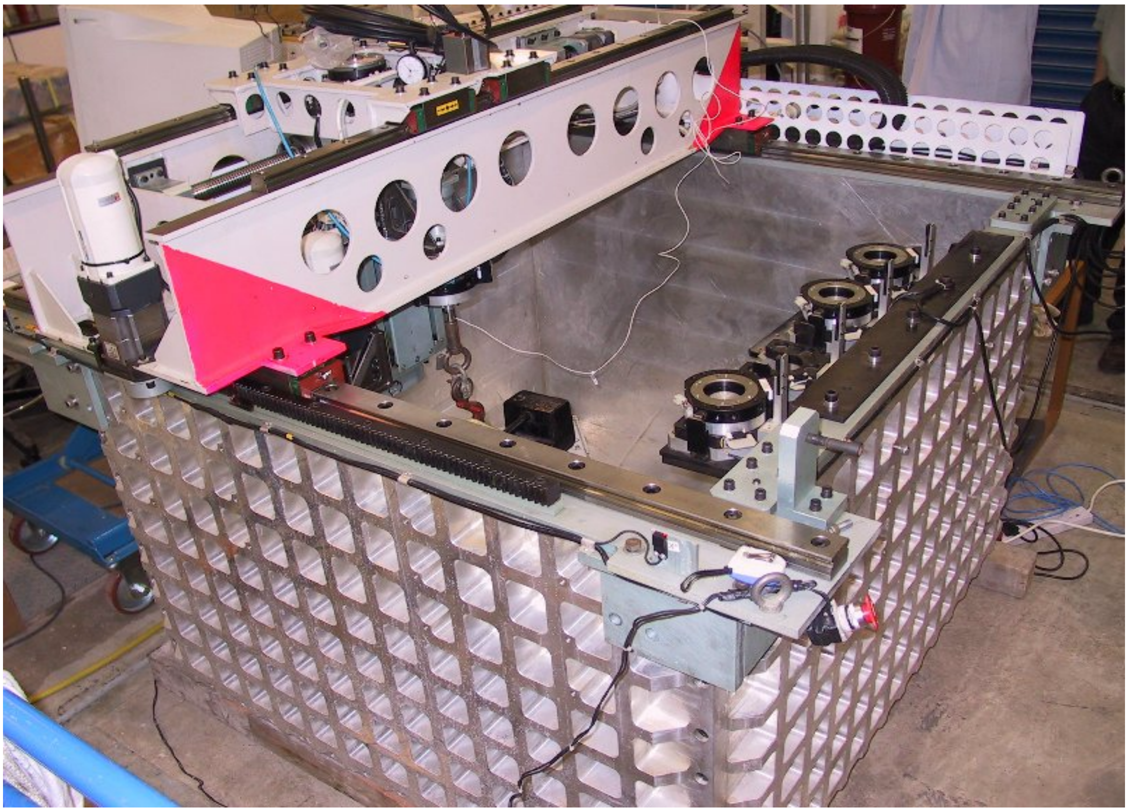


Figure 2. The robotic manipulator in action at 1-g.

Table 1. Main specifications of the 4-axis robotic manipulator

Axis	X	Y	Z	θ
Stroke	875 mm	838 mm	317 mm	270 °
Maximum speed	30 mm/s	30 mm/s	30 mm/s	10 °/s
Accuracy	±1.0 mm	±1.0 mm	±1.0 mm	±1.0 °
Load capacity	±1000 N	±1000 N	±5000 N	±5 N.m

The overall size of the robotic manipulator is strictly constrained by the centrifuge's structural members since no modification of the centrifuge structure is possible. In addition, the maximum mass of the manipulator is limited within 200 kg. Therefore, an innovative custom design was adopted and quality materials with high strength but low density was used for moveable frames. In particular, the motor for the z axis is placed at the side of the axis so as not to occupy vertical room. At the same time, the θ axis is kept as close as possible to the upper end of z axis rail to reduce the bending moment in z axis, and the bending moment and/or torque in the y axis caused by the horizontal load. The structure of the z- and θ-axes is shown in Figure 3.

The manipulator is provided with a standard tool changer to provide capability for changing four different tools without the need for stopping the centrifuge (Figures 1 and 2). The tool changer is capable of accommodating the design loads (Table 1) and provides 6 electrical lines rated at 5 amps, two fluid ports rated at 6 bar, and two fluid ports rated at 100 bar. The tool changer can grab a tool mounted in one of the four tool adapters, move to a specified location, conduct required activities, and move back and change to another tool. A fixture for storing tools while they are not in use is provided. This fixture is located at the extreme end of the x-axis (Figure 1).

2.2 *Control system and man-machine interface*

The sequence of motion is controlled through a ROBotic Control System (ROBCOS). The ROBCOS is comprised of four items: an industrial (PC-type) computer, appropriate I/O and interface hardware (PMAC-Pack Control Board), software for the man-machine interface, and a teaching pendant.

The PMAC-Pack Control Board (also called motion controller) is the kernel of motion control. The function of the controller is to implement interpolation calculation for the tracks of Point to Point (PTP) and Continuous Path (CP) such as line and arc, and then send the calculated results to the drivers to execute the specified movement, as well as to receive data and program input from the operator.

The software for the man-machine interface, which is a well developed Graphical User Interface (GUI), has been implemented as a distributed, object oriented client-server application. Figure 4 shows the main GUI of the software.

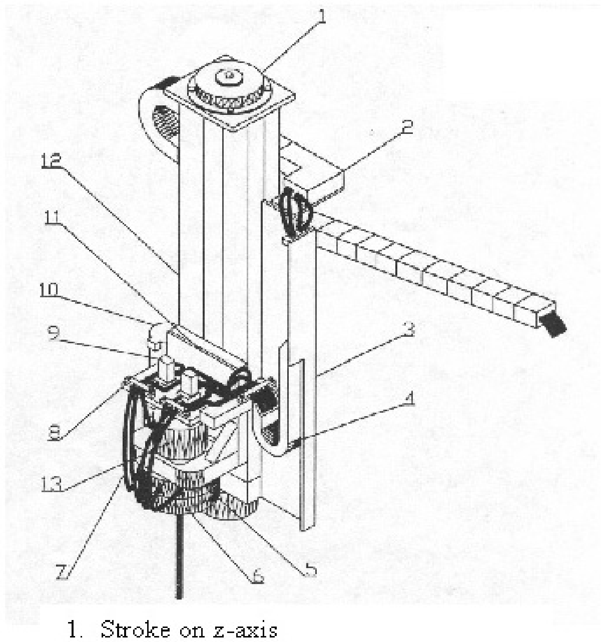


Figure 3. Structural sketch of Z axis and θ axis

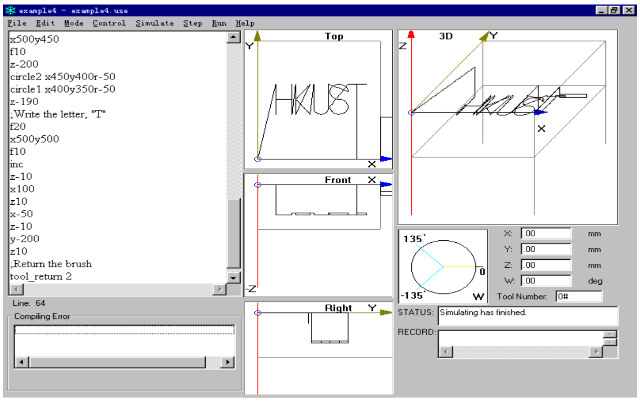


Figure 4. Main GUI of ROBCOS.

Three basic operating modes are provided. In Mode 1 (Edit Mode), the operator enters a sequence of commands, which are stored in a file for future recall. In Mode 2 (Simulation Mode), the operations of the robot are simulated in software. The input may correspond to commands by recalling a file generated in Mode 1 (Programming control), or may be from real-time input by the operator via keyboard

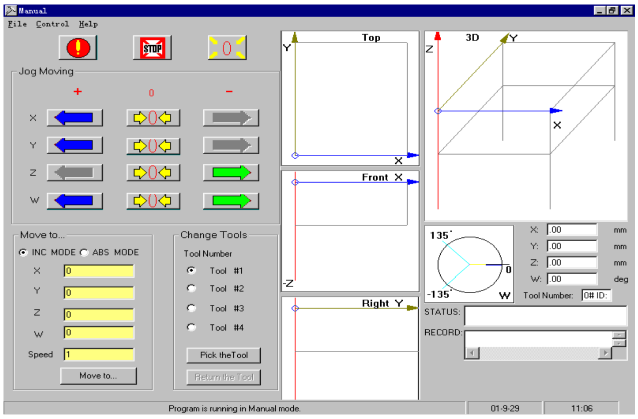


Figure 5. Form of ROBCOS' s manual control.

or teaching pendant (Manual control) (Figure 5). In this mode, the ROBCOS will process the commands without activating the robot; artificial robot position data are created and used to check for programming errors. Mode 3 is Execute Mode, which is similar to Mode 2 except that the operating commands are actually executed by the robot. In brief, the ROBCOS has been well developed so that the robot can be operated and monitored efficiently.

Beyond the three 'basic' modes of operation, several other incidental modes of operation are also provided to implement operations such as pausing or emergently stopping the robot.

By using a distributed client-server object oriented structure, the ROBCOS is capable of communicating with the existing Centrifuge Data Acquisition and Control System (CDACS) (Figures 6 and 7). The CDACS has been designed to permit researchers located at virtually any place in the world not only to observe the test process but also to actively participate in and control centrifuge experiments as they are carried out at HKUST (Figure 7). Participation by remote users is achieved utilizing the internet. Operation of the manipulator is typically be visually monitored using CCTV cameras mounted on the centrifuge and the test package, as well as by real-time display of position data for each the axes on an operator's console.

3 PROSPECTIVE APPLICATIONS

The newly developed 4-axis robotic manipulator offers a powerful in-flight tool for centrifuge modelers to carry out a variety of complex tasks at an elevated g field. The tasks may include excavation and/or fill construction, application of pre-defined horizontal, vertical and torsional loads onto the soil, insertion of measurement probes into the soil model, soil characterization using a CPT at pre-defined locations in the

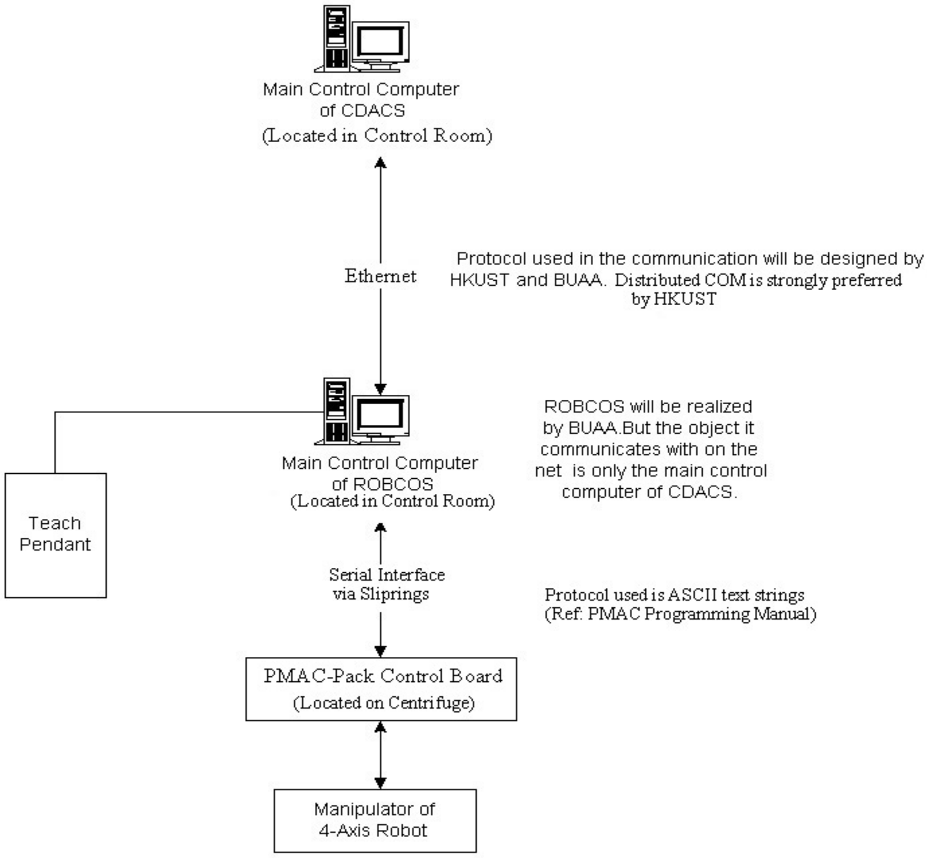


Figure 6. Communication structure between CDACS and ROBCOS.

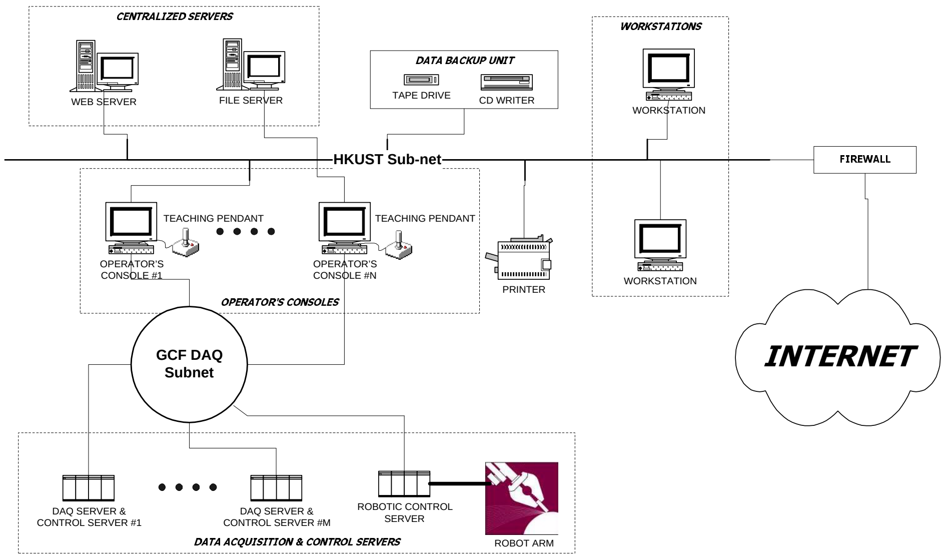


Figure 7. GCF laboratory network topology and structure of CDACS

soil model, carriage of non-contacting displacement sensors for automated scanning measurement of topography of the soil surface, and insertion and/or removal of fluids within the soil model.

The robotic manipulator has been successfully used on the HKUST centrifuge to simulate the correction of an initially tilted building by soil extraction. Figures 8 and 9 show the test set-up and the results, respectively. The test was conducted at 30g. The simulated building had a 5.4 m by 5.4 m base area (prototype) and was approximately 9-story tall (prototype), which generated an average bearing pressure of 89 kPa on the ground. The model ground consisted of a completely decomposed granite (CDG) prepared at a water content of 15.3% and a dry unit weight of 13.0 kN/m^3. A hollow cylinder extracting tool with an external diameter of 30 mm and a soil bin were developed for the test. The movements of the building were measured by two LVDTs and one non-contact laser displacement transducer, and the operation of the robot were monitored by four cameras at different locations.

When the centrifuge was accelerated to 30 g, the building was at an initial tilt of 1/27. To correct the building, some soil was extracted from the ground in the opposite side of the tilt by drilling two series of holes. The sequence of drilling hole is shown in Figure 9. The holes were 160 mm deep and 100 mm away from the building. Each hole was drilled in two steps, each 80 mm depth. Converted to prototype scale, each hole was 0.9 m in diameter and 4.8 m deep, and was 3 m away. At the end of drilling, a trench approximately 0.8 m wide and 6 m long was formed.

Figure 9 shows the variations of building tilt during the soil extraction process. Drilling of the first series of holes (holes #1-4) caused a substantial correction to the building. Particularly, extraction of soil from the bottom half of each hole caused larger movement than that from the upper half of the hole.

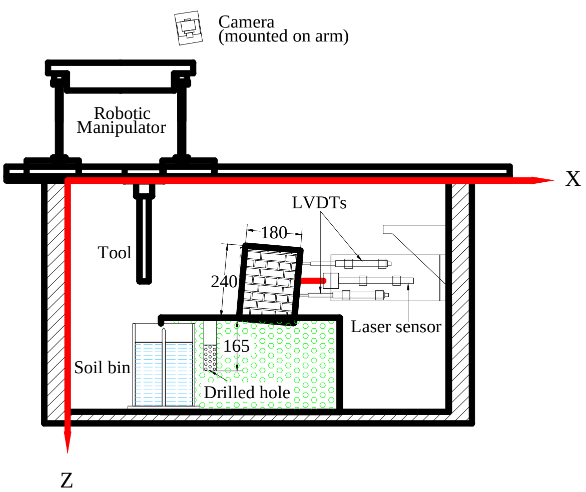


Figure 8. Set-up for simulating tilted building correction using soil extraction (all dimensions in mm)

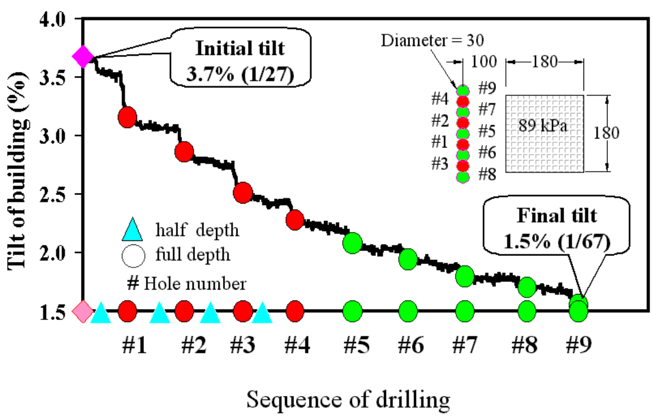


Figure 9. Variation of tilting of model building with soil extraction process (all dimensions in mm)

After drilling nine holes, the final tilt of the building became 1/67. More centrifuge tests with this technique are being conducted at HKUST.

4 CONCLUSIONS

A new 4-axis robotic manipulator has been developed for the HKUST Geotechnical Centrifuge Facility. The innovative design attains the specifications required and makes fully use of the headroom available in the z direction. Quality materials of high strength and light density were used and the total mass of the manipulator is kept below 200 kg.

The Graphical User Interface (UGI) for operators has been well developed so that the robot can be operated and monitored efficiently. By using Distributed Component Object Model, the ROBCOS is capable of communicating with the CDACS, which permits researchers located at virtually any place in the world to not only observe but also actively participate in centrifuge experiments performed at HKUST.

The newly developed 4-axis robotic manipulator provides centrifuge modelers with a powerful tool for in-flight implementation of a variety of complex construction and loading/unloading tasks. Construction activities such as excavation, filling and compaction can be simulated in flight without stopping the centrifuge. The use of the soil extraction technique for correcting a tilted building has been conducted using the manipulator in-flight successfully.

5 ACKNOWLEDGEMENT

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