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MATHEMATICAL MODELING AND VISUAL BASIC SIMULATION FOR POSITION CONTROL OF PLACING BOOM OF CONCRETE PUMP TRUCK

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Abstract. *Concrete pump truck is a type of modern construction equipment used for nonstop concreting. Based on the geometrical relationship of placing boom and kinematics knowledge, this paper builds a kinematics mathematical model for the placing boom operation of concrete pump truck, deduces the relationship between the cylinder stroke and included angle of booms, builds the mathematical model for pouring point track, uses the penalty function method to perform optimal control on the construction control of placing mechanism and carries out position control simulation by means of Visual Basic programming, which lays a theoretical foundation for the intelligent control of placing boom.*
Keywords: Concrete pump truck, Placing mechanism, Position control, Simulation

1. **Introduction.** Concrete pump truck, as shown in Figure 1, is a type of modern construction equipment used for nonstop concreting. The placing boom refers to that on concrete pump truck and the placing intelligentization is a development trend. The so-called intelligentization means the automatic position control of placing boom, that is, the placing boom finishes concreting at the scheduled speed following the scheduled track from one point to another in the space [1]. At present, Putzmeister from Germany is the only company which develops the intelligent placing boom control system. However, it is still at the experimental stage and is far from a real sense of application. Someone in China has been engaged in the research of intelligent placing boom, but they reach the initial theoretical stage on the whole and further perfectness is required. Master Feng and Associate Professor Huang [2] from Changsha University of Science and Technology used a method integrating rigid-flexible coupling model and virtual prototype parametric analysis to perform optimum design on the positions of cylinder hinges, found out the hinge having greater influence on the stress of luffing mechanism of cylinder, carried out optimal combination on the hinge coordinates, reduced the maximum value of its working pressure and performed strength analysis on the optimized arm frame system. Master Yan and Professor Cheng [3] from Jilin University performed finite element analysis (FEA) on the arm frame of HB46 concrete pump, analyzed the hinge link mechanism and lightened the weight of arm frame. Master Tang and Professor You [4] studied the changes of stress when the arm frame of concrete pump was at the most dangerous operating state and performed finite element analysis. Yue [5], a senior engineer, carried out research on the computational analysis of hinge link mechanism of concrete pump truck as well as analysis and experiment on its ultimate stress state. Dai deduced and solved the differential

FIGURE 1. Picture of pump truck

equation of arm frame motion and used power simulation software to establish a rigidity simulation model for arm frame, but did not perform control-related optimized analysis. Qiu [7] researched on the electronically controlled operation technology in terms of intelligent control of arm frame, but failed to study in depth the mathematical module building for position control. For the moment, most of the studies on the arm frame of concrete pump in China focus on the finite elements and link mechanism optimization and there is less research on the control of position and track of placing boom.

In this paper, a mathematic model for typical placing booms is built, an optimized analysis is carried out for construction control and *Visual Basic* is used for simulation programming, which provides a theoretical foundation for the further intelligent control of placing booms.

2. Building a Kinematics Mathematical Model for Placing Boom of Concrete Pump Truck.

2.1. Calculation of rotation angle of placing boom. The placing mechanism can rotate within 360° around the support and the work space of placing boom is three dimensional. The placing boom with n arms has $n+1$ degrees of freedom [8]. After the rotation angle φ of placing boom, the included angle θ_1 between the first arm and the horizontal plane (or stroke b_1 of lifting cylinder of the first arm), included angle θ_i between the arm i and the arm $i-1$ (or stroke b_i of lifting cylinder of the arm i) are given, the position of pouring point of placing boom can be determined exclusively (refer to Figure 2).

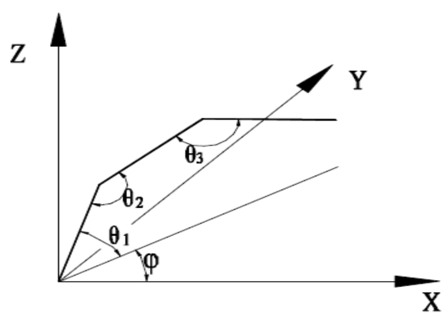


FIGURE 2. Coordinate system of placing mechanism

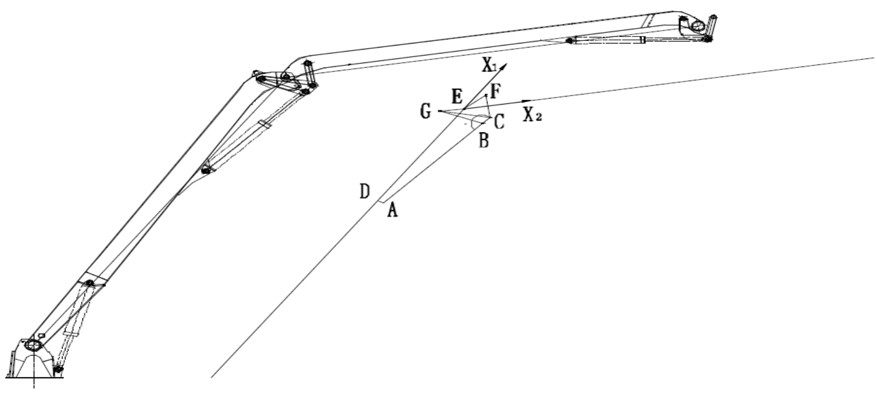


FIGURE 3. Expanded view of the first and second arms

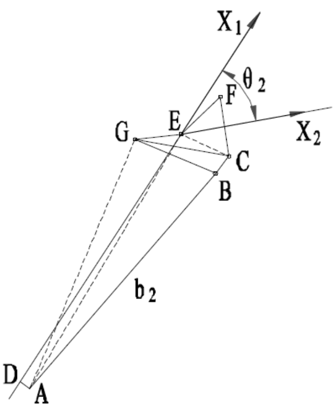


FIGURE 4. Detailed view of the expanded first and second arms

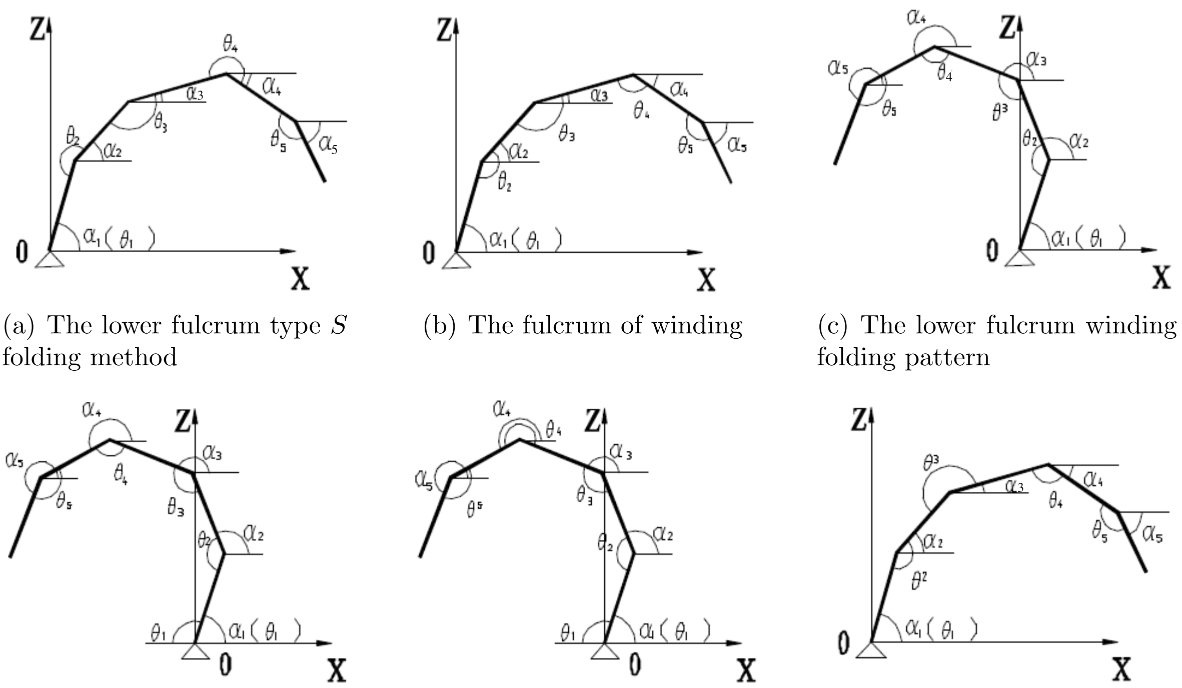
Now, let us take a 37-m placing boom of concrete pump truck for example to explain the geometrical relationship between b_i and θ_i, which can be calculated by specific formulas. In Figure 3, X_1 represents the rectilinear direction of the first arm, X_2 represents that of the second arm and $A, B, C, \ldots, G$ represent the hinges. For easier analysis, refer to Figure 4 for the detailed view of hinges. Segment AB refers to the cylinder length b_2, the change of which can calculate the value of included angle θ_2 between the first and second arms by a trigonometric function.

The following can be derived after trigonometric function conversion:

$$\theta_2 = f(b_2)$$

θ_2 can be solved after the above arithmetic formulas are substituted in succession. The above shows the solution process of θ_2 and those of angles of other arms are similar to it.

2.2. **Calculation of space coordinates of pouring point of placing boom.** The common folding patterns of placing booms are shown in Figure 5 and four types of arms (two to five segments) are available. The diversity of placing booms makes the calculation of hinge positions very complex. Now let us take the lower fulcrum type S as an example to get the calculation formulas for included angles between the arms and the horizontal plane in six folding patterns and those for other folding patterns can be derived in a similar way. Assuming that the placing boom has five sections, the head of concrete pump truck is towards x direction, the bearing center is the origin of coordinates, the elevation direction is the axis z, direction y is $x \times z$, a right-handed cartesian coordinate system. $\alpha_1 \sim \alpha_5$ are positive included angles between the first to fifth arms and the axis x and $\theta_1 \sim \theta_5$ are the first to fifth folding angles.



(a) The lower fulcrum type S folding method

(b) The fulcrum of winding

(c) The lower fulcrum winding folding pattern

(d) The tail fulcrum winding

(e) The lower fulcrum type Z folding pattern

(f) The fulcrum type Z folding pattern

FIGURE 5. Six folding patterns of placing mechanism

As shown in Figure 5(a), the calculation formula for the lower fulcrum type S folding pattern is as follows [9]:

$$\begin{cases} \alpha_1 = \theta_1 \\ \alpha_2 = 2\pi - (\pi - \alpha_1 + \theta_2) = \pi + \alpha_1 - \theta_2 \\ \alpha_3 = \alpha_2 + \theta_3 - \pi \\ \alpha_4 = 2\pi - (\pi - \alpha_3 + \theta_4) = \pi + \alpha_3 - \theta_4 \\ \alpha_5 = \alpha_4 + \theta_5 - \pi \end{cases} \tag{1}$$

After the included angles between the arms and axis x are obtained, the coordinates of hinges can be calculated by the following formula:

$$\begin{cases} P_{ix} = l_i \cdot \cos(\alpha_i) \cdot \cos(\varphi) + P_{i-1x} \\ P_{iy} = l_i \cdot \cos(\alpha_i) \cdot \sin(\varphi) + P_{i-1y} \\ P_{iz} = l_i \cdot \sin(\alpha_i) + P_{i-1z} \end{cases} \quad (i = 1, 2, 3, \dots, n) \tag{2}$$

For easier programming and calculation, now let us take the 4-arm placing boom as an example to express the pouring point coordinates $(x, y, z, 0)^T$ with the following matrix .

$$\begin{bmatrix} x \\ y \\ z \\ 0 \end{bmatrix} = \begin{bmatrix} \cos\alpha_4 \cdot \cos\varphi & \cos\alpha_3 \cdot \cos\varphi & \cos\alpha_2 \cdot \cos\varphi & \cos\alpha_1 \cdot \cos\varphi \\ \cos\alpha_4 \cdot \sin\varphi & \cos\alpha_3 \cdot \sin\varphi & \cos\alpha_2 \cdot \sin\varphi & \cos\alpha_1 \cdot \sin\varphi \\ \sin\alpha_4 & \sin\alpha_3 & \sin\alpha_2 & \sin\alpha_1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} l_4 \\ l_3 \\ l_2 \\ l_1 \end{bmatrix} \tag{3}$$

3. Research on Position Optimization of Placing Boom.

3.1. Building an optimization model for position control of placing boom. Build the kinematics mathematical model for the placing boom of concrete pump truck based on the above to obtain the equations set with the cylinder length b_i and rotation angle φ

of swing mechanism as the variable parameters.

$$\begin{cases} \lambda(\varphi, b_1, b_2, b_3, b_4) = x \\ \omega(\varphi, b_1, b_2, b_3, b_4) = y \\ \phi(\varphi, b_1, b_2, b_3, b_4) = z \end{cases} \tag{4}$$

Formula (4) has multiple solutions, especially when the placing mechanism has more arms ($n = 4 \sim 6$). The construction is controlled automatically. When the pouring point moves along the discrete points of some given tracks, larger solutions for the stroke variations of the arm cylinders may occur after multiple iterative solutions by the above formula even if they are two adjacent pouring points, which may result in problems such as longer time of posture change and greater vibration [10,11]. Therefore, the penalty function method is used for the optimum control of placing mechanism operation.

When the placing mechanism of concrete pump truck moves along the pouring track, its objective function is set as the minimal for the arm cylinders with the highest stroke. Certainly, the optimum objective function may be established by using the driving time of the cylinders or the rotation angle between arms as the measurement objectives and using the least-energy principle. The objective function for the cylinder that is minimal with the highest stroke can be expressed as:

$$\min f(\varphi, b_1, b_2, b_3, b_4) = \min\left[\max(|\Delta b_1|, |\Delta b_2|, |\Delta b_3|, |\Delta b_4|)\right] \tag{5}$$

At the time of placing in a certain area, control realized by Formula (5) can maintain a relatively stable posture of the whole placing mechanism in a certain extent. The objective function for the optimum control of track planning in this paper uses penalty function method and weighting method to build model, i.e., using Formula (5) as the objective and the space geometric position of pouring point as the constraint function. In this way, the optimized objective function becomes:

$$\begin{cases} \min f(\phi, b_1, b_2, b_3, b_4) = \min\left[\max(|\Delta b_1|, |\Delta b_2|, |\Delta b_3|, |\Delta b_4|) + A(|f_x| + |f_y|) \right. \\ \qquad \left. + B|f_z|\right] + C\xi(g_1, g_2, g_3, g_4) \\ f_x = \lambda(\phi, b_1, b_2, b_3, b_4) - x \\ f_y = \omega(\phi, b_1, b_2, b_3, b_4) - y \\ f_z = \varphi(\phi, b_1, b_2, b_3, b_4) - x \end{cases} \tag{6}$$

where A, B and C are penalty functions; Δb_1, Δb_2, Δb_3 and Δb_4 are difference values of strokes of arm cylinders corresponding to two consecutive pouring points and $\xi(g_1, g_2, g_3, g_4)$ is a control function for cylinders with their lengths exceeding the boundary condition. When the cylinder length exceeds the scope defined by the boundary condition, $\xi(g_1, g_2, g_3, g_4) = 1$; otherwise, it equals 0.

Arms of the placing mechanism move simultaneously during actual construction. To lessen the influence of Coriolis force, the weighting method is used to deal with the cylinder stroke and the final optimized objective function becomes:

$$\begin{aligned} \min f(\phi, b_1, b_2, b_3) = & \min\{a|\Delta b_1| + b|\Delta b_2| + c|\Delta b_3| + d|\Delta b_4| + A(|f_x| + |f_y|) + B|f_z|\} \\ & + C\xi(g_1, g_2, g_3, g_4) \end{aligned} \tag{7}$$

In the formula, the relationship $a > b > c > d > 0$ is to assign a greater coefficient to a bigger arm and a smaller coefficient to a smaller arm, in order to reduce the stroke of a cylinder with a bigger arm.

During the actual construction, when the value z in the coordinates of pouring point (x, y, z) is not requested strictly, a pouring height with reasonable change scope may be set to replace f_z in the above Formulas (6) and (7). Therefore, the following equation is established:

$$f_z = \begin{cases} f_z & f_z \geq Z_{\max} \\ 0 & 0 \leq f_z \leq Z_{\max} \\ D & f_z \leq 0 \end{cases} \tag{8}$$

where: D – amount of penalty; $Z_{\max}$ – height set.

3.2. **Optimum control simulation.** In the previous research simulation, mathematical models [12] were obtained based on the types of placing booms and the measurement feedback relationship between the arm motion and angle variation focused on the track control only [13]. No track optimization was carried out or no relation between motion and pumping vibration was studied. In this paper, the simulation of optimum position control is carried out following the principle of minimum cylinder stock maximization.

Based on the above analysis process, this paper uses Formula (7) as the optimized objective function for the optimum control of track planning of the placing mechanism on the concrete pump truck, to perform optimum control simulation of pouring process in a certain given area.

Prior to optimization analysis, input the parameters of position control of placing boom into the *Visual Basic* optimization program as shown in Figure 6. Select the arm's number and types of level in the main menu. Folding patterns of the placing boom are shown in Figure 5 and the commonly-used patterns currently are shown in Figure 7. This *Visual Basic* optimization program shows some universality for the commonly-used patterns.

Three types of levels between arms are available as shown in Figure 8. I type level and III type level are similar except the folding patterns of arms and their function relationship for calculating the rotation angle of arm and cylinder length are basically the same. Therefore, III type level is incorporated to the I type level during the setting of level types.

Next, input the arm lengths and hinge sizes into the *Visual Basic* program. The arm frame model is built by using the upper planes of the arms as the base plane, as shown in Figure 9.

Input the relevant data in Figure 8 into the program. Figure 10 shows an example of arm.

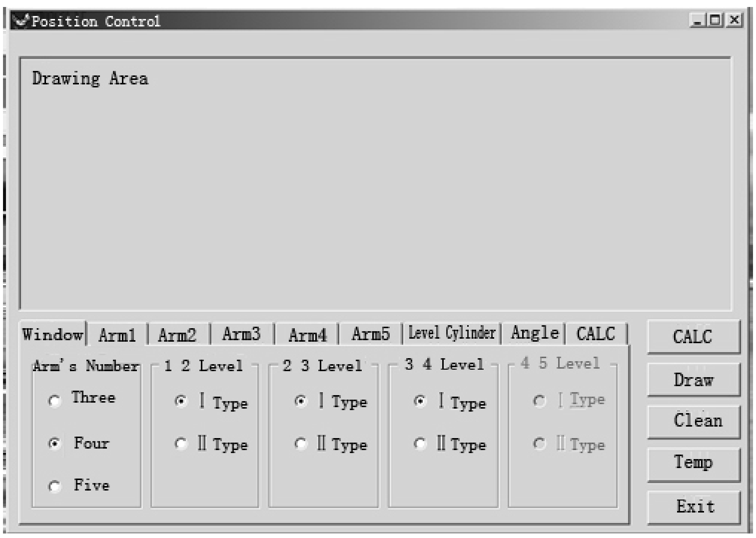


Figure 6. Setting of placing boom folding patterns and level types

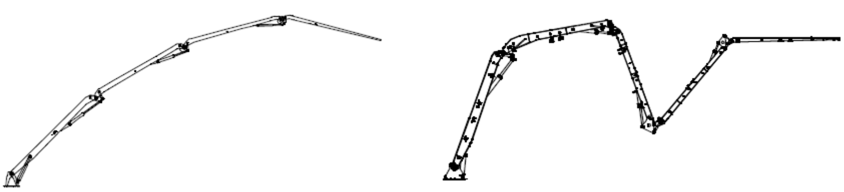


Figure 7. Commonly-used folding patterns of placing boom

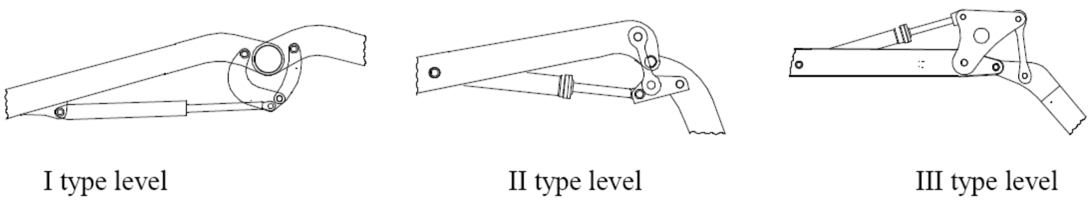


Figure 8. Level types of placing boom

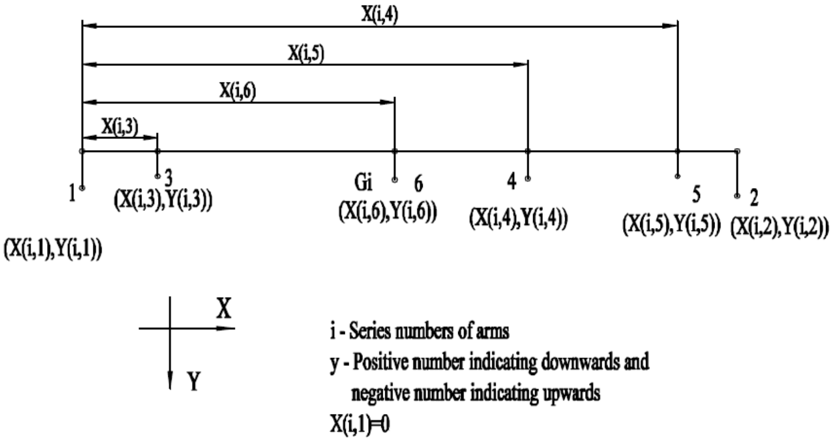


Figure 9. Arm model

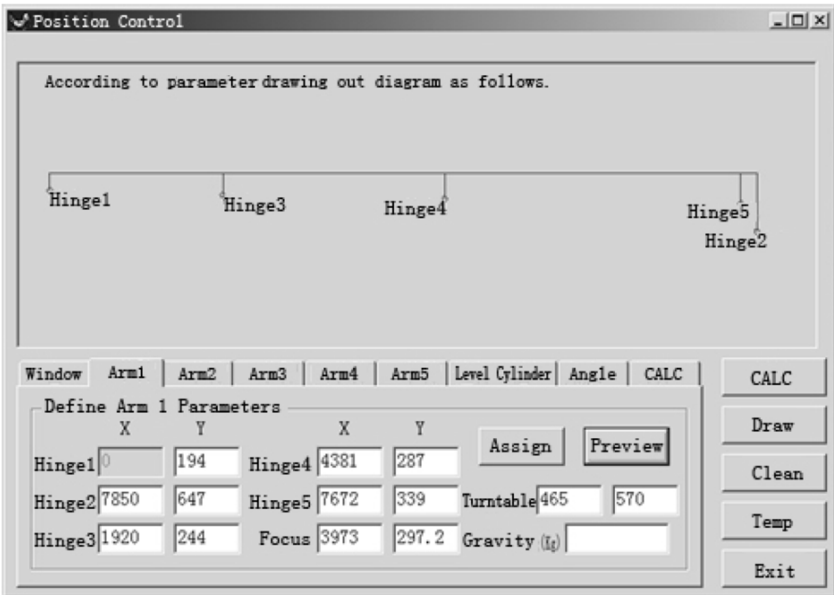


Figure 10. Input of arm frame parameters

After input of all parameters into the program, assign the scope of simulation pouring of the placing boom and obtain the optimum analog simulation of concrete pouring using the optimum Formula (7), as shown in Figure 11. An ideal effect of simulation of placing boom will be obtained in this *Visual Basic* optimization program. There are two kinds of pouring of placing mechanism: one is point-to-point automatic control and the other is the automatic control of given track. As to point-to-point automatic control, relative to the bearing center of placing mechanism, a computer is used to control the stroke of arm cylinders, make the placing boom to operate, perform placing at the pouring points in turn and move from one pouring point to the next. When the pouring point of placing

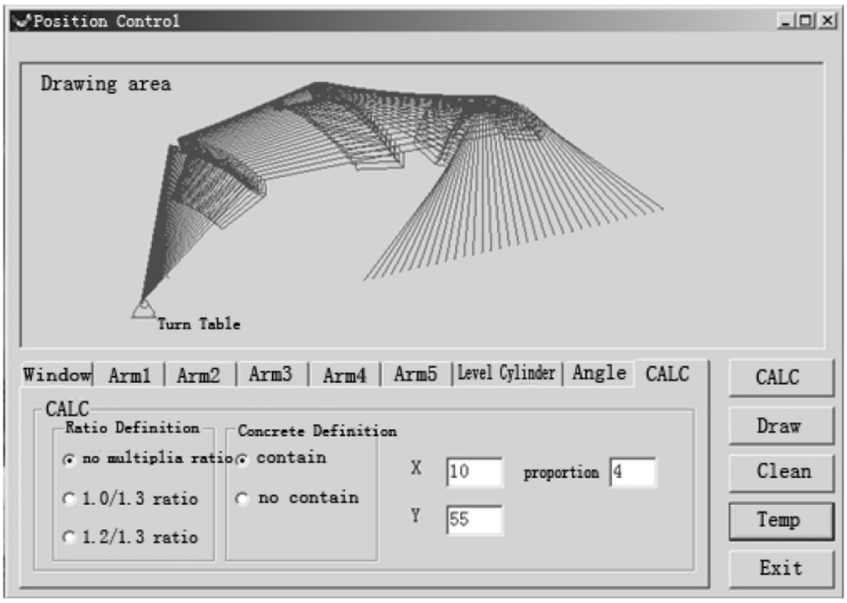


FIGURE 11. Analog simulation of concrete pouring

boom is required to move at the given speed along the given track, the given track may be divided into a series of pouring points by certain step sizes. When the step sizes are as great as an hour, a given track can be approximated. For this reason, the point-to-point automatic control is the foundation for studying the automatic control of placing boom on the concrete pump truck.

If the whole pouring process is automated, the automatic control of concrete pump truck can be regarded as a module. Determine firstly the concrete pouring position, the point track and position point sequence required by output, to serve as the source data for automatic control of placing boom. When the concrete pump truck runs to the required position, the computer will, based on these data, calculate parameters such as time for the movement of cylinders, their stroke amount and stroke positions. Finally, the automatic control command may be formed to drive the operation of cylinders and rotary motor and finish the pouring jobs.

Figure 11 shows the simulation of concrete pouring and the pouring track from one point in the space to another. The figure shows that, the fourth arm has the greatest movement amplitude, the third smaller and the first the smallest, which coincides with Formula (7).

4. **Conclusions.** In this paper, the objective functions and constraint conditions used for optimization calculation are worked out on the assumption that the placing boom is free from obstacle and interference during movement. When taking the possible interference and obstacle met by the placing mechanism into consideration, translate them into the constraint conditions and get the solutions using the above mentioned methods. For this kind of problem, the way to reasonably determine the constraint expression is subject to further study. A rudimentary model for intelligent control is built by means of mathematical modeling and *Visual Basic* simulation, which lays the theoretical foundation for the further intelligent operation.

What we need to do next is to build a physical model to further test the position and track control in order to verify the correctness of mathematic model and provide the theoretical foundation and experiment data for the robotization of concrete pump truck.

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