3D Motion Simulation of Engineering Equipment Working Mechanism Based on Reverse Drive Mode

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Abstract. The working mechanism of engineering equipment has a relatively complicated structure which contains many kinematical pairs, its 3D motion simulation is a difficult problem. Based on the reverse drive mode linked by forward kinematics, 3D motion simulation model of working mechanism is analysed, and the kinematic chains are further established. General procedure of reverse drive mode is summed up, and the establishment strategy of reverse kinematic chain is expounded. This paper discussed these problems of adjusting motion axis and restraining DOF in reverse drive mode, and illustrated the controllers which control the form of 3D motion simulation. Through the above method, the 3D motion simulation of the working mechanism is realized. The analysis indicates that the 3D motion simulation of engineering equipment working mechanism based on reverse drive mode have more flexible use, convenient control and lifelike simulation result.

1. Introduction
The engineering equipment training can transform from real equipment training means to informatization means by constructing virtual training system, and there are great significance to the improvement of equipment support ability. The 3D motion simulation of engineering equipment working mechanism in virtual training system is generally more complex than others. It not only involves 3D geometric models, but also considers the dynamic changes of its position, motion, collision and deformation in the virtual scene. These problems are also the difficulties in the current virtual training system. The simulation of the interaction between model objects can be realized correctly and effectively by reasonably describing the pose of the objects, establishing the model of kinematic chain and the relationship between fit and constraint. The general 3D motion simulation approach is forward drive mode, which is to drive driven link in the kinematic chain to motion accordingly by the motion of driving link. In reverse drive mode based on destination oriented, the position and motion mode of driven link is determined first, and then the motion and position of other components including driving link in the kinematic chain are inversely calculated. Reverse drive mode is often easily used compared with forward drive mode, which can quickly create 3D movement of complex mechanism, improve design efficiency, and more intuitively verify the interaction effect of the designed mechanism members.

2. Establishment of 3D Motion Simulation Model of Working Mechanism
2.1. Mechanism Motion Analysis
Taking the motion of the working system of a certain engineering equipment as an example, the working system is composed of working mechanism (turning frame, arm, etc.), hydraulic system (hydraulic
cylinder, control valve, etc.) and control system, which is used to complete the working movement such as turning, unfolding or folding and laying down or uplifting, as shown in figure 1. The turning frame is fixed on the front end of the roof deck of the equipment body by two pins, which is used to turn metal girders. The turning frame can achieve a maximum rotation of 80°. The arm which is connected to the turning frame by two pins is used for laying down and uplifting metal girders.

![Figure 1. Working mechanism](image1.png)

![Figure 2. Movement diagram](image2.png)

The 3D motion simulation of erection system is built on the basis of its motion mathematical model, and the device can be simplified into two crank-shanking mechanism: the turning mechanism and the laying down mechanism, as shown in table 1.

| Mechanism     | Member                      | Form                | DOF (Degree of Freedom) |
|---------------|-----------------------------|---------------------|-------------------------|
| 1 turning     | turning frame, cylinder, piston, frame | crank-shanking mechanism | 1                       |
| laying down   | arm, cylinder, turning frame | crank-shanking mechanism | 1                       |

The DOF of the whole working mechanism is 2, and the cylinders of the working mechanism are the driving links to drive and realize the given motion.

The movement diagram of a single crank-shanking mechanism can be simplified as shown in figure 2. A single crank-shanking mechanism is composed of crank, link and shanking. The connecting rod (piston rod) is the driving link, which moves in the shanking block (oil cylinder) and pushes the crank (turning frame) to rotate at a certain Angle.

As shown in figure 2, the crank radius is \( R \), and the distance between the point \( O_1 \) and \( O_2 \) is \( L \). When the working length of the connecting rod (the distance between the cylinder fulcrum and the fulcrum between the piston rod and the turning frame) is \( l \) at any moment, the position equation of a crank shanking mechanism is:

\[
\begin{align*}
R \cos \alpha - L &= l \cos \beta \\
R \sin \alpha &= l \sin \beta
\end{align*}
\]

\( \beta \) and \( l \) can be obtained from formula (1):
\[ \beta = \arctan 2\left[ \frac{R \sin \alpha}{R \cos \alpha - L} \right] \]  
\[ l = \left( R^2 \sin^2 \alpha + (R \cos \alpha - L)^2 \right)^{1/2} \]  

The variation of \( \beta \) and \( l \) can be set to design the motion simulation of working mechanism from the perspective of motion simulation. However, the calculation of this method is relatively complex and the process is tedious. If the design is combined with the reverse driving mode, the 3D simulation process will be more flexible. Not affecting the motion simulation effect, the driving link is changed from original piston to crank, that is to say that forward drive mode is transformed into reverse drive mode. Reverse drive mode starts from child object rather than parent object. Change the drive to a crank here. The crank rotates as a driving link, so the (Angle \( \alpha \)) can be easily controlled in motion design. Angle \( \alpha \) can be obtained from formula (3):

\[ a = \arccos \frac{R^2 + L^2 - l^2}{2RL} \]  

2.2. Establishment of Kinematic Chain Based on Hierarchical Relationship

Because there are few members that move independently in mechanism, the movement of most members is restricted by other members or coordinated with other members to form various kinematic pairs (such as revolute joints, sliding joints, etc.). The whole mechanism is a kinematic chain system composed of several members connected by kinematic pairs and based on object hierarchical model.

When the mechanical device of engineering equipment realizes complex virtual movement simulation, its linkage relation is different from that of the real mechanism. This link relation is designed to simplify the process and facilitate the implementation of 3D motion simulation by linking objects together to form a virtual kinematic chain based on hierarchical relationship. Membership can be created by linking one object to another. In a linked chain, the movement of one chain may affect some or all of the chains, and the transformation applied to the parent object will also be passed to the child object. For the needs of simulation training, the mechanism motion model is transferred according to the hierarchical relationship of "driving link \( \rightarrow \) driven link" or "parent object \( \rightarrow \) child object", then kinematics chain is formed, as shown in figure 3.

The kinematics chain may consist of one or more sub-kinematics chains to form a complex linkage system. After establishing kinematic chain, it is convenient to determine the planning of object (member) action sequence, and it is also beneficial to control mechanism simulation movement. For example, it can affect the pose of child member by changing the pose of parent member, while the change of the pose of child member will not affect parent member.

3. Reverse Drive Mode

3.1. General Procedure of Reverse Drive Mode

Reverse drive mode using goal-oriented method reverses the direction of the kinematic chain based on hierarchical relationship, which can be used to locate the target object and set the position and direction of the end of the chain. It directly drives child member instead of parent member, and calculates the position and direction of the members in this kinematic chain through reverse calculation according to the kinematic link relation. In this way, the motion of the parent member is affected step by step, and finally parent member follows the motion of the child member. In this system, the whole kinematic chain system can move only by the motion of one child member in the kinematic chain. Its control program is shown in figure 4.
3.2. Establishment Strategy of Reverse Kinematic Chain

Reverse drive mode starts with and based on links and pivot positions, then two principles should be considered. Kinematic pairs are constrained by specific position and rotation properties, and the position and direction of parent member are determined by the position and direction of the child member.

Several kinematic chains can be created throughout the hierarchical instead of just one according to the mechanism motion complexity of engineering equipment. Of course, several separate hierarchy can also be created, rather than linking all the members together in one large hierarchy, as shown in figure 5.

3.3. Adjusting the Motion Axis

An obvious advantage of reverse drive mode is that it is possible to define the working states of kinematic pairs. Kinematic pairs is actually at the pivot point of the member. The pivot point can be
moved to change its actual position and direction relative to the member itself, as shown in figure 6. The working state control of kinematic pairs is actually to restrict the DOF of the member relative to the position and direction of the pivot point. Adjusting the pivot point of a member does not affect any child members that are linked to this member.

Axial, angular, or distance limits can be added to kinematic pair being defined. Moreover, the motion simulation can be made vivid by setting the priority order and resistance of kinematic pairs.

3.4. Restriction of DOF
Revolute joints, sliding joints have 3 DOF respectively. In reverse drive mode, the DOF direction of child member is set relative to the local coordinate axis of the parent member. The range of motion or rotation allowed on the active axis can be set a limit. For example, the piston can only slide within the length of the cylinder. Resistance can be used on the entire range of joint motion or rotation which simulating the natural effects of joint friction or inertia.

3.5. Determining Controller
Controller can store the values of moving key points, store the relevant settings of the program, and interpolate the values of moving key points. Track curve in x, y and z directions of controller is shown in figure 7. Controllers generally include floating point controller, Point3 controller, position controller, rotation controller, scaling controller, transformation controller, etc. As a position controller, Bezier controller is used to handle in most 3D motion simulation. Bezier controller can control acceleration, delay, and other types of motion by interpolating between key points of smooth curves. Euler XYZ is a common rotation controller whose rotation is divided into three separate "Bezier floating point" tracks. Angle α of the crank can be easily controlled by Euler XYZ in motion design.

![Figure 7. Track curve.](image)

3.6. Calculation of Kinematic Chain in Reverse Drive Mode
In general, the object which rotate uniformly or move straight can be selected as the virtual driving member, so that its motion can be conveniently set and controlled, and then the motion process of other members in the kinematic chain can be determined through reverse calculation.
4. Conclusion
The forward drive mode uses a top-down approach, which starts from the position and direction of the parent member, and then goes to the position and direction of each child member hierarchy. So hierarchical linking should be in the order from parent hierarchy to child hierarchy. Axis points define joints between members. Child member inherits the transformation of the parent member.

Reverse drive mode is based on the concept of reversing kinematic chain, and the motion process of other members in the kinematic chain can be determined by one child member through reverse calculation. The solution is only to calculate the set key points, and all other motions are used by interpolation method. For more accurate result, all key points of the specified range can be also solved. Reverse drive mode is easier to use than forward one, which can quickly create complex motions. Of course, two modes should be combined to control the 3D motion simulation of engineering equipment complex mechanism more flexibly.

5. References
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