Automatic Metal Drum Opening-sealing Device Prototype for Nuclear Power Plant

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Abstract
Automatic metal drum opening-sealing device is the key device of the low and intermediate level radioactive wastes treatment line for the nuclear power plant, which is used to open and seal the metal drum filled with radioactive wastes automatically. This paper firstly analyzes the key technologies of the metal drum opening-sealing device which include the technology of metal drum positioning, drum trip bolt and bolt hole positioning, drum cover depositing and bolt tightening shaft torque controlling. Then, based on the modular design method, a device prototype was designed and made and tests were carried out based on the prototype. The test results verified the design rationality and high operation efficiency of the prototype.

Key words: Metal Drum; Automatic Opening-sealing; Modular; Bolt Tightening Shaft; Torque Control

1. INTRODUCTION
Cement solidification line is used for the collection, temporary storage, curing (or fixing) of radioactive solid wastes (waste resins, concentrates and scrap filter cartridge) generated during the process of operation and maintenance of nuclear power plants, which firstly makes the radioactive solid wastes into stable solidified body by stirring and mixing it well with cement and then stores it temporarily and disposes of it later (Deters, Secco and Wuerdemann, 2013).

Automatic opening-sealing device is the key equipment of cement solidification line, which is used to automatically open and seal the 400L metal drum filled with radioactive wastes (Christian Deters, Hak-Keung Lam, Emanuele Lindo Secco and Helge, 2015). The key technologies used to develop automatic opening-sealing devices include the technology of metal drum body and drum cover center positioning, drum cover bolt and bolt hole positioning, drum cover depositing, precise controlling of bolt unscrewing and tightening torque and other key technologies (Wolf and Lorenz, 2011). At present, the representative companies engaged in research and development of the device are Bilfinger Berger and Siempelkamp from Germany, Westinghouse from America and so on. The automatic opening-sealing device manufactured by these companies all can automatically open and seal the metal drum but they have different characteristics and some different functions due to different design philosophy and experiences (Cammarata, 2015). Take the function of drum cover depositing as an example, the device produced by Bilfinger Berger does not have this function, but that produced by Siempelkamp deposits the drum cover by lifting of manipulator, and Westinghouse deposits
through chain drive. Meanwhile, there is few published information related to such devices in order to keep technology secret or due to other reasons (Hu, Rong, Ying g, Franke, Hribernik and Thoben, 2014).

In terms of the above situation, we propose an independently developed design method of automatic opening-sealing device prototype in this paper (Hu, Rong, Ying, Franke, Hribernik and Thoben, 2014). Based on the design idea of modular, the automatic opening-sealing device is composed of the bracket, translational module, lifting module, rotation module, drum cover depositing module and tightening shaft module(Xu, 2003). Flexible positioning method is used for metal drum body and drum cover center positioning, and unpowaered drum cover depositing rack is used for depositing several drum covers, enhancing the reliability of mechanical systems(He, Shen, Yu, Feng and Song, 2013). Meanwhile, elastic shaft structure is adopted at the middle of the independently developed tightening shaft, which can automatically apply a compressive force to the bolt for making tightening easy, and flexible joint design is adopted at the front-end which can adapt to bolts of different angles and thus avoiding seizure(Morawiec, 2013). Moreover, the introductions of an adaptive control method makes the independently developed tightening shaft can achieve precise controlling of bolt tightening torque(Fujinaka, Nakano and Omatu, 2007). Finally, prototype experiment is conducted to test the performance of the prototype, which verified the rationality of the design(Tareq S. El-Hasan, Patrick C. K. Luk, Bhinder and Ebaid, 2000).

2. OVERALL FUNCTION OF THE DEVICE

Automatic opening-sealing device is located at the above of transmission line of conveyor belt of cement solidification line, as shown in Fig.1. When metal drums are transported to the position below the automatic opening-sealing device by transmission line, the automatic opening-sealing device will automatically open or seal the drum cover according to remote control commands after positioning and tightening of metal drum. Thus, the workflow of automatic opening-sealing device is as follows: (1) conduct 400L metal drum and drum cover center positioning; (2) perform drum cover bolt positioning; (3) tightening shaft unscrews the bolt; (4) the cover removal manipulator grips the drum cover and the lifting mechanism drives the manipulator to separate the drum cover from drum body; (5) deposit drum cover; (6) conduct reverse operation of the workflow after the drum is filled with cement and re-seal the drum body with drum cover.

![General Layout of Cement Solidification Line](image1.png)

![Metal Drum (400L)](image2.png)
And the operation target of automatic opening-sealing device is as shown in Fig.2, which is a metal drum of 400L.

3. KEY TECHNOLOGIES FOR AUTOMATIC OPENING-SEALING DEVICE

The most critical technologies for the operation of automatic opening-sealing device are: (1) drum center positioning; (2) bolt and bolt hole positioning; (3) the continuous depositing of drum cover; (4) precise controlling of bolt tightening torque.

3.1. Drum Center Positioning

The positioning principle is as shown in Fig.3, which firstly moves the rotating mechanism by translational mechanism in the direction perpendicular to the direction of conveyor (namely X direction, and Y direction is the direction of conveyor, the same below), and the X direction positioning sensor (laser sensor) installed above the air-actuated gripper for gripping drum scans drum body chord length during the movement. Then, the positioning of the X direction drum center is realized by comparing the difference between the drum body chord length obtained by scanning and the fixed chord length of the position where lies the air-actuated gripper.

In the X-Y plane, set the coordinates of the center of the rotation mechanism as \( P_1(x, y) \), and the center coordinates of the drum as \( P_2(x, y) \), and the goal of positioning the X direction center is to determine \( P_2(x) \) and let:

\[
P_2(x) = P_1(x) \tag{1}
\]

Let the X direction positioning sensor scans the coordinates \( P_1(x_1) \) and \( P_1(x_2) \) of drum edge in turn and then the chord length \( L \) of drum body is thus measured to be:

\[
L = P_1(x_1) - P_1(x_2) \tag{2}
\]

The chord length of rotating mechanism in the same direction of where positioning sensor lies is a fixed value \( C \), whereas the difference \( D \) between the coordinate of rotating mechanism in the X direction and the center of the drum is:

\[
D = \frac{1}{2}(C - L) \tag{3}
\]

Thus currently, the X direction coordinate of drum center is:

\[
P_2(x) = P_1(x) - D
= P_1(x_1) - \frac{1}{2}[C - (P_1(x_1) - P_1(x_2))] \tag{4}
\]

Then, the positioning of X-direction of metal drums can be realized by moving the coordinates of rotating mechanism to \( P_2(x) \).

![Figure 3. Drum center positioning principle](image-url)
located at the position of floating connection locks the position, and then the automatic alignment of rotating mechanism and the center of the drum in the X-Y plane is done.

3.2. Bolt and Bolt Hole Positioning

The principle of bolt and bolt hole positioning is shown in Fig.4 and Fig.5, respectively. Bolt positioning is realized by the high-precision laser sensor mounted on the air-actuated gripper. When conducting bolt positioning, the air-actuated gripper grips the drum body and the rotating mechanism circularly rotates around the flange edge of drum body. And the rotary motor stops working when the controller receives the signal of laser sensor, and then the positioning is done, whereas the accuracy of bolt positioning is jointly ensured by the laser sensor, the mounting position of tightening shaft and the flexible sleeve at the front end of tightening shaft.

![Figure 4. Sketch map of bolt positioning](image)

![Figure 5. Sketch map of bolt hole positioning](image)

3.3. Drum Cover Depositing

The metal drum opening-sealing device produced by Siempelkamp deposits the drum cover by lifting of manipulator which has freedom of translational and rotational motion, and thus the complexity of mechanism is intensified(Yu and Chen, 2014). However, drum cover depositing of the device manufactured by Westinghouse is realized by chain drive to stack, while the sensor detects the number of drum cover deposited(Wang, 2012). In general, these two mechanisms have both increased the complexity of the design and control of systems(Li, Nan Ding and Cao, 2011). In this paper, the device is designed with a non-powered depositing method, taking the initial position of the device as a fixed coordinates for depositing drum cover. Meanwhile, the number of drum cover deposited is determined by the stroke of lifting mechanism, and a fixed angle of rotation is performed each time when depositing the drum cover, in order to avoid the interference of bolt in different drum covers, as shown in Fig.6. In all, the overall structure of the device is simple and effective, and does not require power and sensor devices.

3.4. Torque Control

In actual operation, the bolt should be screwed into the bolt hole to the specified torque. At first, a simple switch control method is adopted in the previous tests, i.e., by comparing the dynamic torque sensed by sensor on the tightening shaft and the set tightening torque, the tightening of the bolt is accomplished when the set torque is reached and the tightening shaft stops working. However, because this method only defines the target torque and it controls by tightening shaft driving constant speed control of motor, the tightening shaft cannot
immediately stops working when the actual torque reaches the set torque. Therefore, in the case of high motor speed setting, serious over-torque will appear, thus causing damage to the bolt, drum cover and drum body joints, which must be avoided in the application of nuclear waste storage container. Meanwhile, in the process of tightening the bolt, it is difficult to establish a precise mathematical model of tightening torque and angle of bolt feed due to the impacts of the material of bolt and contact surface, friction coefficient, viscosity coefficient of the system and other factors.

In view of the above problems, an adaptive backstepping controller is designed to control the tightening process. By combining the mathematical model of tightening shaft drive motor (DC servo motor), speed reducer and the tightening process, the tightening process model can be obtained as follows:

\[
T = \frac{K_c}{n} \omega_m + f(T)
\]

\[
\dot{\omega}_m = -\frac{1}{J} (B\omega_m + \frac{n}{T} + K_c) i
\]

\[
i = -\frac{R \omega_m}{L} - \frac{K_c}{L} + \frac{1}{L} u
\]

Here, \(T\) is the output torque of tightening shaft; \(K_c\) is the unknown constant; \(n\) is the reduction ratio of speed reducer for tightening shaft; \(\omega_m\) is the mechanical angular speed of the drive motor; \(f(T)\) is the nonlinear function of \(T\); \(J\) is the equivalent moment of inertia for motor output shaft; \(B\) is the viscous friction coefficient of the motor; \(K_c\) is motor torque constant; \(R\) is the armature winding resistance; \(L\) is inductance of the armature winding; \(K_e\) is the back-EMF coefficient of motor and is the armature voltage.

The Matlab simulation results of the adaptive backstepping controller derived on the basis of model (5) is shown in Fig.7, and the derivation process is ignored here due to limited space. In this simulation, the unknown constant is defined to be \(K_c = 0.1\), and non-linear function \(f(T) = \sin(T)\).

**Figure 6.** Comparison of scheme for drum cover depositing module

(1) Depositing module of automatic metal drum opening-sealing device produced by Westinghouse (2) Sketch map of non-powered depositing

**Figure 7.** Simulation of torque output
4. DESIGN OF PROTOTYPE

4.1. Modular Structure

In the modular design of the system, the system is divided into several modules by functional decomposition of the mechanism and the structure of the system is shown in Fig.8. Meanwhile, based on the modular design principles and the connecting structure between modules, the system is decomposed into a common module, a fixed module, a universal interface and a fixed interface. Moreover, the bracket module and drum cover depositing module do not need electronic control universal interface because there are no drive and sensor devices. And the driving mechanisms of translational module and lift module are the same, using the same drive module. Other modules are designed according to the specific requirements and the principle of easy to disassemble and maintain.

4.2. Overall Design of Prototype

At first, three-dimensional virtual design of the automatic opening-sealing device is conducted based on the functions the device means to realize, and the overall effect of three-dimensional assembly is demonstrated in Fig.9.
4.3 Bracket Module

The structure of bracket module is as shown in Fig.9, constituting mechanical frame of the device. Meanwhile, the entire bracket can be partially disassembled to make transportation and assembly easy. The bracket module is used to support and connect with other functional modules to accomplish fixation and installation of the device.

4.4 Translational Module

The structure of translational module is as shown in Fig.10. This module enables the translational motion of support platform in the XY direction. Meanwhile, the total stroke in the X direction is of 1057mm, and the positioning slider in the Y direction makes the lift module above it have a floating stroke of 10mm.

![Figure 10. Translational Module](image)

4.5. Lifting Module

The structure of lifting module is as shown in Fig.11. Lifting module is mounted on the translational mechanism with a 10mm floating freedom in the limited scope of the direction of the conveyor. Moreover, the lift module drives the rotating module to do lifting within the stroke of 360mm.

![Figure 11. Lifting Module](image)

4.6. Rotating Module

The structure of rotating module is as shown in Fig.12. The module is driven by the rotary motor modules, including servo motors, gears and speed reducer, and the total rotating stroke is of 201 degrees. Rotating module is one of the four main function modules of automatic opening-sealing device, and the other three are positioning module, drum cover removal module and tightening shaft module.
The sub-module of cover removal module is included in the rotation module. Cover removal module is composed of three air-actuated grippers which are equipped with mechanical position-limit parts of uniform length. Thus, the change of position of the drum body and drum cover center, which is caused by different pop-up speed or different stroke of gripper cylinder when cover removal air-actuated grippers grip the drum cover, can be effectively avoided.

Tightening shaft module is as shown in Fig.13, which takes the servo motor as its power unit, and the reducer and coupling as its transmission components, and the dynamic torque sensor as its real-time torque detection unit, and makes the spring, adjusting sleeve and the front end sleeve adapt to the adjustment of bolt at the front end. Due to the presence of the spring, the adjusting sleeve has a certain degree of stretching freedom, facilitating the tightening of bolt and avoiding shaking of bolt. Meanwhile, the front end sleeve is a universal joint which can be adapted to different angles of bolt deflection, and can traps the bolt in the deviation range of 5 mm.

4.7. Drum Cover Depositing Module

The structure of drum cover depositing module is as shown in Fig. 14, which can simultaneously deposit many drum covers. The mounting position of drum cover depositing plate is corresponded to the initial position of automatic opening-sealing device, i.e., the center of drum cover depositing plate and the center of the rotation mechanism at the initial position is aligned, so that the center of drum cover depositing plate and drum cover can be automatically aligned every time when depositing drum cover as long as the rotating mechanism returns to the initial position. Meanwhile, the number of drum cover deposited can be obtained by measuring the stroke of lifting module, and there will be difference of a fixed angle between the two successive strokes of rotating module when depositing the following drum cover, which effectively avoids the interference between the upper and lower drum cover bolt. Moreover, because air-actuated grippers are equipped with mechanical position-limit parts, it can be ensured that the drum cover will not shift. In all, this module does not require power and its structure is simple and effective.
4.8. **Prototype Demonstration**

The automatic metal drum opening-sealing device prototype developed by Center for Robotics from University of Electronic Science and Technology of China is demonstrated in Fig. 15.

![Prototype Demonstration](image)

**Figure 15.** Metal drum Automatic opening-sealing device prototype

5. **PROTOTYPE TESTING**

A standard 400L metal drum, which is actually used in nuclear power plants, was adopted for conducting prototype testing. After testing, it is verified that the prototype can automatically open and seal the drum cover, continuously deposit drum cover, automatically adapt to the position of metal drum within the range of 50mm in the X direction and 10mm in the Y direction, and the bolt tightening torque is accurate. And the specific prototype operating parameters are shown in Table 1.
Table 1. Performance testing of the prototype

<table>
<thead>
<tr>
<th>Test Item</th>
<th>Performance parameters of automatic metal drum opening-sealing device</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test Value</td>
</tr>
<tr>
<td>Stroke of translational mechanism</td>
<td>1057mm</td>
</tr>
<tr>
<td>Speed of translational mechanism</td>
<td>25mm/s</td>
</tr>
<tr>
<td>Accuracy of translational mechanism</td>
<td>0.1mm</td>
</tr>
<tr>
<td>Stroke of lifting mechanism</td>
<td>360mm</td>
</tr>
<tr>
<td>Speed of lifting mechanism</td>
<td>10mm/s</td>
</tr>
<tr>
<td>Accuracy of lifting mechanism</td>
<td>0.1mm</td>
</tr>
<tr>
<td>Stroke of rotating mechanism</td>
<td>201°</td>
</tr>
<tr>
<td>Speed of rotating mechanism</td>
<td>5°/s</td>
</tr>
<tr>
<td>Accuracy of rotating mechanism</td>
<td>0.2°</td>
</tr>
<tr>
<td>Positioning in the Y direction</td>
<td>10mm</td>
</tr>
<tr>
<td>Deviation of tightening shaft adapt to bolt</td>
<td>5mm</td>
</tr>
<tr>
<td>Deviation of bolt adapt to bolt hole</td>
<td>2mm</td>
</tr>
<tr>
<td>Maximum load of gripper</td>
<td>100kg</td>
</tr>
<tr>
<td>Output torque of tightening shaft</td>
<td>50Nm</td>
</tr>
<tr>
<td>Time for tightening bolt</td>
<td>21s</td>
</tr>
<tr>
<td>Time for unscrewing bolt</td>
<td>12s</td>
</tr>
<tr>
<td>Time for opening drum cover</td>
<td>4min20s</td>
</tr>
<tr>
<td>Time for sealing drum cover</td>
<td>4min10s</td>
</tr>
</tbody>
</table>

The operation process of prototype testing is shown in Fig.16.

Table 2. Bolt tightening test of different control methods

<table>
<thead>
<tr>
<th>Control method</th>
<th>Performance parameters of different control methods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tightening time</td>
</tr>
<tr>
<td>Switch control (with motor speed of 3000 rpm)</td>
<td>12s</td>
</tr>
<tr>
<td>Adaptive fuzzy backstepping control</td>
<td>20s</td>
</tr>
<tr>
<td>PID control</td>
<td>23s</td>
</tr>
<tr>
<td>Switch control (with motor speed of 1667 rpm)</td>
<td>27s</td>
</tr>
</tbody>
</table>
Figure 16. Functional Testing of the Prototype. (1)Starting device (2)Positioning drum center (3)Unscrewing bolt (4)Gripping drum cover (5)Depositing drum cover (6)Positioning bolt (7)Positioning bolt hole (8)Process of tightening bolt (9)Bolt tightened.

Figure 17. Comparison of torque output with different controlling method. (1) Torque with switch control (with motor speed of 3000 rpm) (2) Torque with adaptive backstepping control (3) Torque with PID control (4) Torque with switch control (with motor speed of 1667 rpm).

In prototype testing, the specified torque of 50Nm was defined as the target to compare the switch control method mentioned in section 2.4 and the adaptive tightening method using four different methods to control the tightening shaft in tightening bolt. In the test we set 50Nm torque as the target of the bolt tightening torque. The test results show that the final value of tightening torque is much higher than that of the set torque when using switch control under the condition of high motor speed, whereas the tightening of bolt with switch control is slow under the condition of low motor speed, and there is still over-torque phenomenon. The PID control method gets a better output performance but the bolt tightening speed is also slow and the final torque is 50.9Nm. However, the precise control of torque can be achieved with adaptive controller, moreover, the tightening speed can also be ensured. The test results are demonstrated in Table 2 and Figure17.
6. CONCLUSION

(1) The design of the overall mechanical structure is reasonable and continuous automatic drum cover opening and dealing can be achieved, and the reliability of the device is enhanced to some extent with the use of non-powered drum cover depositing module.

(2) The adopted mechanical structure which can move in the Y direction makes the device automatically adapt to the position of metal drum to the greatest extent allowed by the conveyor, and thus accurate and reliable positioning can be realized.

(3) Bolt and bolt hole positioning are achieved by mounting laser sensors on the air-actuated gripper, which is simple and accurate.

(4) Flexible joints are used for the front end sleeve of tightening shaft, which can adapt to bolt positional deviation to some extent, and the adaptive torque control method used can realize precise controlling of the output torque.

REFERENCES


