Simulation Platform of Monitoring and Tracking Micro System for Dangerous Chemicals Transportation

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Abstract—Real test method of monitoring and tracking micro system for dangerous chemicals transportation has many disadvantages: long test cycle, high test cost, high test risk and bad reproducibility. Aimed at these disadvantages, a simulation platform which can be used for the simulation test of monitoring and tracking micro system is developed. This simulation platform is composed of motion simulator and simulation environment. The motion simulator is a kind of parallel robot with Hexaglide structure and has a total of 8 degrees of freedom (DOF). This parallel simulator cannot only realize the motion simulation of yaw, pitch and roll, but also provide pure linear motion in the Y direction, which is significant for the acceleration or deceleration simulation. The simulation environment is developed with a sealed cavity, in which a steel tank is used to simulate the tanker for dangerous chemicals transportation. The environment parameters such as temperature, humidity, concentration of combustible gas, the pressure and liquid level in tank can be measured and changed. Based on the motion simulator and the simulation environment, motion parameters such as position, attitude, angular rate, velocity and acceleration and the environment parameters can be measured simultaneously by micro system and standard sensors. With the comparison of these measured data, the micro system can be validated. This simulation platform provides a good test method for the monitoring and tracking micro system and has important significance for dangerous chemicals transportation.

Index Terms—motion simulation, environment simulation, dangerous chemicals transportation, micro system, parallel platform

I. INTRODUCTION

Dangerous chemicals include explosive, compressed or liquefied gas, combustible gas or liquid and poisonous gas or liquid [1, 2]. Due to the development of industrialization, the production and transportation of dangerous chemicals increases rapidly. In China, the annual transportation capacity of dangerous chemicals is more than 400 million tons [3]. About 22000 companies produce dangerous chemicals and more than 28000 enterprises engage in relative businesses [4]. Therefore, the security situation of dangerous chemicals transportation becomes very severe [5, 6]. As the dangerous chemicals are inflammable, explosive, corrosive or poisonous, their transportation has significant risk of fire, explosion, leakage or poisoning. In recent years, several accidents of dangerous chemicals transportation on highway occurred, resulting in huge economic loss, environment pollution and abominable society influence. According to the statistics of the U.S. Department of Transportation, more than 13000 accidents relevant to dangerous chemicals transportation happened in 2011 [7].

In order to reduce the accidents of dangerous chemicals transportation, protect the environment and people's life, the monitoring and tracking micro system for dangerous chemicals transportation is researched [8, 9]. The micro system can be integrated in the tanker or ships to realize the monitoring and tracking of the transportation for dangerous chemicals [10, 11]. Usually, the test of monitoring and tracking micro system is realized by installing the test system in the tanker or ship and then testing it on real road transportation or sea transportation. This method has the advantage of good authenticity, but has many disadvantages also: long test cycle, high test cost, high test risk and bad reproducibility.

Aimed at the disadvantages of real test method, based on the support of High Technology Research Development Program of China (863 Program), a simulation platform for dangerous chemicals transportation is developed. This simulation platform is used to provide good experimental platform and simulation environment for the simulation tests of the micro system, which can realize the monitoring and tracking of the transportation for dangerous chemicals. In this paper, the structure and kinematics analysis of motion simulator is introduced in Section II and Section III respectively. In Section IV, the hardware of the simulation environment is proposed. The development of gas sensor module is presented in Section V. In Section

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VI, the software of the simulation environment is introduced and some experiment results are shown.

II. STRUCTURE OF MOTION SIMULATOR

A. Mechanical Structure of Motion Simulator

Aimed at the test requirements of monitoring and tracking micro system for dangerous chemicals transportation, the simulation platform needs to realize not only the motion simulation of the tanker but also the environment simulation of road transportation. Thus the simulation platform is composed of two parts: motion simulator and simulation environment. The former is used to simulate the motion of tanker which is loaded with dangerous chemicals. The motion parameters includes: position, velocity, acceleration, attitude and angular rate. The latter can simulate the transportation environment of dangerous chemicals. The environment parameters includes: temperature, humidity, concentration of combustible gas in environment, pressure in tanker and liquid level of the liquefied combustible gas in sealed tanker.

Generally, the motion simulator adopts the 6-DOF (degrees of freedom) parallel Stewart platform [12, 13]. As shown in Figure 1, this kind of parallel motion simulator can simulate vehicles' yaw, pitch and roll and other action in the traveling of tanker [14, 15]. However, as the limitation of its working space, it is hard to maintain a long time in the simulation of acceleration or deceleration.

Aimed at this shortcoming, the motion simulator for dangerous chemicals transportation is designed based on another parallel structure. As shown in Figure 2, the parallel motion simulator adopts Hexaglide operation structure [16]. The mechanical structure of this motion simulator mainly includes 6-DOF upper plate, hook joint of upper plate, linkage, hook joint of kinematic pairs and the kinematic pairs. The 6-DOF upper plate is linked to 6 kinematic pairs by hook joints of upper plate, linkages and hook joints of kinematic pairs. The lengths of 6 linkages are equal. Each kinematic pair consists of screw, guide and slide. The screw of the kinematic pairs is connected to AC servo motor. The 6-DOF motion of motion simulator can be realized through the linear motion of 6 kinematic pairs driven by AC servo motors. The 6 guides of this motion simulator are parallel to each other and in the same plane. Therefore, this motion simulator has the advantage that it not only can realize the 6-DOF motion, but also can provide pure linear motion in the Y direction. And the movement distance is only restricted by the length of guides. Thus the workspace of motion simulator can easily to extend in this direction. When the moving direction of tanker is consistent with the Y direction, the acceleration or deceleration simulation of tanker will have longer distance and providing better motion simulation for dangerous chemicals transportation.

In order to realize the environment simulation of road transportation, a sealed cavity is designed and fixed in the upper plate of 6-DOF motion simulator. The environment sensors and the monitoring and tracking micro system are integrated in the sealed cavity. The environment parameters within sealed cavity can be tested by those sensors. And various environments in the road transportation of dangerous chemicals can be simulated by regulating the environment parameters. Generally, the angular displacement of yaw and roll of 6-DOF parallel motion simulator is comparatively small. Two DC servo motors, which are the yaw driven motor and the roll driven motor, are added to increase the motion displacement of the sealed cavity. The test of micro system for dangerous chemicals transportation can be realized by this simulation platform with the 6-DOF motion simulator for motion simulation and the sealed cavity for environment simulation.

B. Control System of Motion Simulator

The motion simulator has 6 AC motors and 2 DC motors. The control system of motion simulator is developed to realize the close-loop control of 6 AC motors and 2 DC motors. As shown in Figure 3, the control system consists of industrial control computer, motion controllers, motor drivers and motors. After the power amplification of AC motor drivers, the output signals of a 4-axis motion controller and a 2-axis motion controller are transferred to 6 AC servo motors, which are used to drive the 6-DOF Hexaglide parallel simulator. In order to realize the servo control of two DC motors: the roll driven motor and the yaw driven motor of the sealed cavity, an additional 2-axis motion controller is utilized. With the commands from industrial control computer, the
coordinate motion control of these 8 motors can be performed by the motion controllers.

The industrial control computer is the main control unit of this control system. Its functions includes: providing human-man interface, kinematic analysis of the simulator, path planning and sending command and motion parameters to motion controllers.

The functions of motion controller includes: accepting the command and motion parameters from industrial control computer, command transformation, obtaining the position and velocity feedback of motors and producing velocity pulse signals and direction pulse signals to motors.

This control system developed with industrial control computer and motion controller features simple structure, high stability and high reliability.

III. KINEMATICS OF MOTION SIMULATOR

The number of DOF of the motion simulator with parallel structure can be computed by following formula:

\[ F = 6(n - g - 1) + \sum_{i=1}^{g} f_i - F_0 \]  

where \( n \) is the total number of components, \( g \) is the total number of kinematic pairs, \( f_i \) is the number of DOF of the kinematic pair \( i \) and \( F_0 \) is the number of redundant DOF of the parallel structure.

According to the mechanical structure of motion simulator, the total number of components is 14, the total number of kinematic pairs is 18, the total number of DOF of kinematic pair is 36 and the simulator hasn’t redundant DOF. Thus, the number of DOF of the motion simulator can be derived as following:

\[ F = 6(14 - 18 - 1) + 36 - 0 = 6 \]  

With the analysis of DOF and mechanical structure of motion simulator, the kinematic model is built. As shown in Figure 4, the base coordinate system \( B \) is the global reference coordinate system, the origin of the coordinate system \( M \) of upper plate is located in the center of upper plate and each slide has its coordinate system \( S_i \) (\( i = 1 \) to 6). In the motion simulation of transportation for dangerous chemicals transportation, we first define the position and attitude of upper plate based on the position and attitude of tanker in road transportation, and then send command to the AC motors driving the kinematic pairs and thus realize the motion simulation. In other words, the motion of simulator is based on the position of point \( o_i \) (\( i = 1 \) to 6) which are the center point of slide coordinate systems. In order to derive the position of each slide, the inverse kinematic analysis is needed. If the center position of upper plate in respect to the global reference coordinate system is expressed as:

\[
T = \begin{bmatrix}
1 & 0 & 0 & x \\
0 & 1 & 0 & y \\
0 & 0 & 1 & z \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  

And the attitude of upper plate in respect to the global reference coordinate system can be expressed using Euler angle \((\phi, \theta, \psi)\). Then, the attitude of upper plate can be derived by following steps:

1. rotating the base coordinate system around its axis \( z \) by angle \( \phi \);
2. rotating the new coordinate system around its axis \( x \) by angle \( \theta \);
3. rotating the new coordinate system around its axis \( y \) by angle \( \psi \).

Thus the homogeneous matrix of the attitude transformation from base coordinate system to upper plate coordinate system can be expressed as following:

\[
R = R(\phi) \cdot R(\theta) \cdot R(\psi)
\]

\[
\begin{bmatrix}
C\phi C\psi & -S\phi S\psi C\theta & -C\phi S\psi + S\phi C\psi S\theta & 0 \\
S\phi C\psi & C\phi S\psi C\theta & S\phi S\psi C\psi + C\phi C\psi S\theta & 0 \\
0 & -C\phi S\psi & C\phi C\psi & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  

where \( C\phi \) is \( \cos \phi \), \( C\theta \) is \( \cos \theta \), \( C\psi \) is \( \cos \psi \), \( S\phi \) is \( \sin \phi \), \( S\theta \) is \( \sin \theta \) and \( S\psi \) is \( \sin \psi \).

Then, the position and attitude of upper plate can be represented by

\[
T_u = T \cdot R
\]

\[
\begin{bmatrix}
C\phi C\psi & -S\phi S\psi C\theta & -C\phi S\psi + S\phi C\psi S\theta & x \\
S\phi C\psi & C\phi S\psi C\theta & S\phi S\psi C\psi + C\phi C\psi S\theta & y \\
0 & -C\phi S\psi & C\phi C\psi & z \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  

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As shown in Figure 5, the upper plate is an enneagon and the position \( P_i' \) \((i=1 \text{ to } 6)\) of each hook joint of upper plate in respect to upper plate coordinate system is fixed.

\[
A = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\[P_i' = \begin{bmatrix}
1 & 0 & 0 & r \cos \alpha_i \\
0 & 1 & 0 & r \sin \alpha_i \\
0 & 0 & 1 & 0
\end{bmatrix}\]

\[
\begin{pmatrix}
inP \backslash x \\
inP \backslash y \\
inP \backslash z
\end{pmatrix} = A \begin{pmatrix}
0 \\
1 \\
0
\end{pmatrix}
\]

where \( r \) is the radium of enneagon and \( \alpha_i \) \((i=1 \text{ to } 6)\) represents the central angle between hook joint \( P_i \) and axis \( x \).

Thus the position of each hook joint in respect to the global reference coordinate system can be computed by

\[
P_i = T_M \cdot P_i'
\]

And, the center position of slide coordinate systems \( S_i \) can be defined by

\[
O_i = \begin{bmatrix}
1 & 0 & 0 & o_{i,x} \\
0 & 1 & 0 & o_{i,y} \\
0 & 0 & 1 & 0
\end{bmatrix}
\]

where, the value of \( o_{i,x} \) is constant and related to the distance between the guides.

Because the length of each linkage of the motion simulator is constant, the displacement of each slide can be derived by

\[
\|P_i - O_i\| = l_i
\]

where \( l_i \) \((i=1 \text{ to } 6)\) is the length of linkage \( i \) and all equals to constant \( l \).

IV. HARDWARE OF SIMULATION ENVIRONMENT

A. System Structure of Simulation Environment

The simulation environment is developed to providing a test environment for the micro system, which is used to monitor and track the transportation of dangerous chemicals. As shown in Figure 6, the system structure of simulation environment is a kind of distributed system. The upper level computer is the industrial control computer and the lower level computer is the embedded controller based on C8051 micro processor. The upper level computer includes information display module and data storage module. The main function of information display module is receiving measured data from each standard sensor and micro system in the sealed cavity, and synchronously displaying the measured data through the forms of value and visualization curve respectively. At the same time, all the measured data are stored in the hard disk of industrial control computer by the data storage module. These data can be used for further analysis of the simulation platform.

The sealed cavity is used to construct the simulation environment for dangerous chemicals transportation. In the sealed cavity, there are embedded controller, sealed tank, environment adjusters, micro system and standard sensors. The embedded controller is the core processor of the sensor data sampling and environment parameter adjusting. The sealed tank which is loaded with water and fixed in the sealed cavity is used to simulate the tanker filled with liquefied combustible gas. As the temperature and humidity is always changed in the transportation of dangerous chemicals, the temperature and humidity of the simulation environment can be regulated by the embedded controller and environment adjuster. The concentration of combustible gas in the sealed cavity can be adjusted to simulate the leakage of combustible gas loaded in tanker. And, the pressure and liquid level of the liquefied combustible gas in the sealed tank can be regulated too. The motion parameters, such as the angle of yaw, pitch and roll, the angular rate, the velocity and acceleration of X, Y and Z direction, and the environment parameters, such as temperature, humidity, concentration of combustible gas, pressure and liquid level, are sampled by standard sensor and micro system respectively. The data of micro system and sensors are transmitted to upper level computer through CAN bus and serial interface, and the validity of micro system can be verified by the comparison with standard sensors.

B. Integration of Simulation Environment

After the integration of simulation environment, the inner structure and outer structure of sealed cavity are shown in Figure 7 and Figure 8 respectively. All standard sensors, including inertial sensor, temperature sensor, humidity sensor, pressure sensor, liquid level sensor and combustible gas sensor, are integrated in the sealed cavity.
The cavity also provides enough space for the fixing of micro system. There is a steel sealed tank in the cavity. This sealed tank is used to simulate the tanker for dangerous chemicals transportation. The diameter and height of steel tank are 300mm and 500mm respectively. The pressure sensor and liquid level sensor are installed in the steel tank. In our project, the dangerous chemicals mainly include liquefied petroleum gas (LPG) and liquefied natural gas (LNG). The steel tank is filled with water and high-pressure air which are used to simulate the LPG or LNG. The value of pressure and liquid level can be easily changed by injecting water or high pressure air into the sealed tank through valves. A heating membrane is fixed on the inner surface of cavity. The environment temperature in the sealed cavity can be regulated by the heating membrane.

![Figure 7. Inner structure of simulation environment.](image)

![Figure 8. Outer structure of simulation environment.](image)

The inertial sensor, which is fixed on the bottom of sealed cavity, is NAV420CA and produced by Crossbow Company. The NAV420CA is a combined navigation and attitude and heading reference system that can measure stabilized pitch, roll and yaw angles and angular rate in a dynamic environment along with GPS-based position, velocity and acceleration. The measured data of NAV420CA inertial sensor is transferred to the industrial control computer through the serial interface. As the space limitation of sealed cavity, the inertial sensor is not installed in center point of the bottom. However, after a simple coordinate transformation, the motion of the sealed cavity can be computed by the attitude, velocity value and acceleration value of the inertial sensor.

Combustible gas sensor module is used to measure the gas concentration of simulation environment. The sensor is TGS6812 and produced by Figaro Company. This sensor is a kind of catalytic type gas sensor. It features high accuracy, good durability and stability, quick response, and linear output. Gas concentration can be obtained by the embedded controller based on TGS6812 and Wheatstone bridge. If the concentration exceeds the set value, it means that leakage is occurring in the transportation of dangerous chemicals.

The standard temperature and humidity sensor are installed in the top of cavity so as to measure the temperature and humidity in sealed cavity. The humidity value in sealed cavity is regulated by controlling humidifier. In order to install and integrate the sensors and micro system in the sealed cavity conveniently, the sealed cavity is designed to be a composite structure which consists of base and cover. The base is made of steel and stiff enough to sustain the sealed tank, sensors and other parts. The material of cover is glass fiber reinforced plastic. This kind of material not only ensures the stiffness of the cover but also reduces the weight of the sealed cavity.

V. DESIGN OF COMBUSTIBLE GAS SENSOR MODULE

A. Structure of Combustible Gas Sensor Module

The combustible gas sensor module is shown in Figure 9. This sensor module is based on TGS6812 and has small size. Its length and width is 55mm and 42mm respectively. The sensor TGS6812, which is based on catalyst combustion principle, is the core of this module. This sensor possesses an adsorbent inside its sensor cap, its cross sensitivity to alcohol is much smaller than traditional catalytic type sensors. It can detect not only hydrogen, but also methane and LPG. As the main component of LNG is methane, this sensor provides an excellent solution for monitoring gas leakage in the transportation of LPG or LNG.

![Figure 9. Combustible gas sensor module.](image)

The TGS6812 sensor is comprised of two components: the detecting element and reference element. The former is sensitive to combustible gases and the latter is not sensitive to gases. When combustible gases are present, they will be combusted on the detecting element, causing its temperature to rise. And accordingly the resistance of this element will increase. Thus, we can use three high-precision resistances with this sensor to construct a Wheatstone bridge. By measuring the voltage of out-of-balance signal, the concentration of combustible gas can be derived. The output voltage is sampled by A/D converter ADS1110. This chip is a precision converter with differential inputs and up to 16 bits of resolution in a
small package. After the A/D conversion of the ADS1110, the sample data can be transmitted to an embedded controller by I²C-compatible serial interface. As the operation voltage of sensor is 3.0V and the power is 5.0V, a voltage regulator is used to realize the voltage conversion.

B. Experiments of Combustible Gas Sensor Module

In order to establish the corresponding relationship between the sample value of combustible gas sensor module and the real gas concentration in the environment, the calibration of combustible gas sensor module is needed. As the main components of LNG and LPG are methane and propane respectively, the methane and propane with purity up to 99.9% are selected as standard gases and the calibration of sensor module is realized with HPR-20 mass spectrometer system. In order to verify the stability of the combustible gas detection module, the measure experiments with standard methane and propane are carried out after one week. Figure 10 shows the standard value and the measured value of sensor module with methane. And Figure 11 shows the error between standard value and measured value. Figure 12 shows the standard value and the measured value of sensor module with propane. And the error between standard value and measured value is shown in Figure 13. The results show that this combustible gas sensor module based on TGS6812 has good linearity and precision.

VI. SOFTWARE OF SIMULATION ENVIRONMENT

A. Software of Lower Level Computer

The lower level computer of the control system of simulation environment is the embedded controller. It is developed based on the C8051F040 microcontroller using C language. Its software structure is based on modularization and shown in Figure 14. It is composed of main loop, CAN bus communication module, AD conversion module, the I²C bus communication module and the I/O control module.

The resolution of AD converter module is 12 bits. It is used to complete the acquisition of two-wire analog input of the temperature sensor, humidity sensor, pressure sensor and liquid level sensor. The I/O control module are used to control the on and off of the relays, achieving the adjustment of temperature, humidity, pressure and gas concentrations in the sealed cavity. The AD acquisition resolution of the combustible gas detection module is 16 bits. And the transmission of gas concentration data from the TGS6812 sensor to controller is based on the I²C bus communication modules.
module is used to communicate between the controller and the host computer, and its data transmission rate is up to 1Mbit's.

B. Software of Upper Level Computer

The software development of upper level computer is based on the Windows platform using VC++ 6.0. The software can display the real-time value of sensors in each simulation environment. The data of standard sensors and micro system are transferred to upper level computer based on CAN bus and serial interface. In order to improve the reliability, the software is developed using modular design method. The entire software system is divided into the CAN bus communication module, temperature display module, humidity display module, pressure display module, the gas concentration display module, liquid level display module and data storage module. The data of the sensors collected by the embedded controller is sent to the host computer through the USB-CAN converter card. After the data processing, the data of sensors and micro system are stored in hard disk of host computer in the form of TXT by the data storage module. At the same time, the sensor data will be displayed in the two forms of value and visualization curve respectively by the data display module. As part of Human-Machine Interface of upper level software, the experiment curves of temperature, humidity, pressure, liquid level and gas concentration are shown in Figure 15.

VII. CONCLUSION

Aimed at the disadvantages of real test method, a simulation platform for dangerous chemicals transport is developed. The simulation platform consists of motion simulator and simulation environment. The motion simulator is a kind of parallel platform with Hexaglide structure and has a total of 8 DOF. In contrast to Stewart platform, this parallel platform has longer distance for the acceleration or deceleration simulation of tanker and providing better motion simulation for dangerous chemicals transportation. The simulation environment is constructed in a sealed cavity, which is fixed on the upper plate of motion simulator. The environment parameters: temperature, humidity, concentration of combustible gas, the inner pressure and liquid level of tank can be regulated by embedded controller. Besides the environment parameters, the motion parameters such as position, attitude, angular rate, velocity and acceleration can be measured by the standard sensors and micro system simultaneously. The micro system can be validated by the data comparison. This platform providing a good test method for the monitoring and tracking micro system and has important significance for dangerous chemicals transportation.

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