Embedded Control System for Six-DOF Electro-hydraulic Motion Platform

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ABSTRACT: Six-degree-of-freedom electro-hydraulic motion platform (SEMP), which is an integration of a mechanical system, a hydraulic system and a control system, is kind of a high performance equipment. The control system is the core component of SEMP. But controllers for SEMP now are commonly motion controllers or industrial control computers, which are expensive, large and inconvenient. In this paper, a SEMP is established and the main parameters of the SEMP are shown. Based on a real-time operating system μC/OS-III,
embedded control system, which has advantages of cheap to buy, easy to manufacture and, small and convenient to move, is designed. And the main design schemes of hardware and software are shown in allusion to functional modules of the control system. The whole system including the test rig of the SEMP, the embedded control system and an upper computer is established. System trajectory experiments are carried out. The results show that the embedded control system designed can totally meet the control demands. This embedded control system designed has good interactivity, flexibility and performance.

1. INTRODUCTION
The 6-degree-of-freedom electro-hydraulic motion platform (SEMP), which is an integration of a mechanical system, a hydraulic system and a control system and also known as Stewart, is kind of a high performance equipment. It has been widely used in vibration isolator, ankle telerehabilitation and displacement measuring device. S. Pedrammehr [1] established a Stewart platform-based machine tool table and analyzed the vibrations of the parallel manipulator. M. Girone [2] established a Stewart platform-based system for ankle telerehabilitation. Boyin Ding [3] proposed a novel Stewart platform-based manipulator with decoupled sensor-actuator locations. Andrea Mura [4] built a six-DOF displacement measuring device based on a modified Stewart platform.

A control system is the core component of SEMP and a mature embedded control system is desirable. At present, the hydraulic servo controllers are commonly motion controllers and industrial control computers, which are expensive, large and inconvenient. Ye, J. [5] proposed a hybrid trigonometric compound function neural network for a nonholonomic mobile robot based on MATLAB xPC Target. Kai, Gao, C. [6] did hybrid position/force control of 6-dof hydraulic parallel manipulator based on two personal computers. Li, Y. [7] did force tracking control in human-robot collaboration based on an industrial computer. Liu, G. [8] did some tracking performance experiments of an electrohydraulic Gough-Stewart platform by using MATLAB xPC Target.

Embedded systems have been widely used due to its obvious advantages of low cost and power consumption, small volume and convenience. But there are fewer mature embedded controllers for SEMP now. In this paper, based on a real-time operating system µC/OS-III, an embedded control system for SEMP is proposed. The embedded control system is cheap and convenient compared with these common used control systems.

2. System description of SEMP

2.1 Description of SEMP
Fig. 1 presents the SEMP utilized in this paper. The hydraulic power mechanism is composed of hydraulic cylinders and electric hydraulic servo valves. The motion of the hydraulic cylinder is controlled by the controller which controls the input current of the servo valve.

Fig. 1 Basic machine of SEMP
The specific index parameters are shown in Table 1.
Table 1. Index parameter of SEMP

| Index  | Shift       |         |         |
|--------|-------------|---------|---------|
|        | Vertical    | Horizontal | Heave   |
| Pose   | ±0.25m      | ±0.25m  | ±0.175m |
| Velocity | 0.5m/s    | 0.5m/s  | 0.4m/s  |
| Acceleration | 0.5g    | 0.5g    | 0.5g    |

Rotation

| Index  | Roll      | Pitch    | Yaw   |
|--------|-----------|----------|-------|
| Pose   | ±15°      | ±15°     | ±30°  |
| Velocity | 20°/s    | 20°/s    | 20°/s |
| Acceleration | 60°/s² | 60°/s²   | 60°/s² |

The following two coordinate systems are built. The moving coordinate system is built on the upper platform and the origin is at the center of the upper platform. The static coordinate system is fixed on the earth. At the initial position, the static coordinate system is completely coincident with the moving coordinate system, as is shown in the Fig. 2.

In Fig. 2, A₁ to A₆ are the upper hinge points of the six hydraulic cylinders. B₁ to B₆ are the lower hinge point. A₁B₁ to A₆B₆ are the six hydraulic cylinders. O is the origin of the moving coordinate system. O is the origin of the static coordinate system. l₁ is the distance between A₁ and A₂, A₃ and A₄ or A₅ and A₆, which are the upper hinge points of the six hydraulic cylinders. l₁ is the distance between B₂ and B₃, B₄ and B₅ or B₆ and B₁, which are the lower hinge points of the six hydraulic cylinders. l₁ is the distance between A₂ and A₃, A₄ and A₅ or A₆ and A₁, which are the upper hinge points of the six hydraulic cylinders, l₁ is the distance between B₁ and B₂, B₃ and B₄ or B₅ and B₆, which are the lower hinge points of the six hydraulic cylinders. l₁ is initial distance between one of upper hinge points and the corresponding lower hinge points. h₁ is the distance between the upper hinge points and the center of the mass of the upper platform. h is the distance between the lower hinge points and the center of the mass of the upper platform.
Lower hinge point  

Base  

A1(A6) A3(A4)  

h1  

l2  

Upper platform  

A2(A5)  

Hydraulic cylinder  

B1(B6) B2(B5) B3(B4)  

Fig. 2. The sketch map of structure parameter of SEMP

The parameters of SEMP are shown in Table 2.

Table 2. The parameters of SEMP

| Parameter | l1 (m) | l2 (m) | l3 (m) |
|-----------|--------|--------|--------|
| Value     | 0.8783732 | 1.1 | 0.14 |

| Parameter | l1 (m) | h1 (m) | h (m) |
|-----------|--------|--------|------|
| Value     | 0.2 | 0.055 | 1.168 |

2.2 Inverse solution

Let matrix $A$ be the coordinate vector of the upper hinge points $A_i (i=1, 2, \ldots, 6)$. The three elements at the first row, second row and third row of the first column are the coordinates of X axis, Y axis and Z axis in the moving coordinates. The rest is same as above. Then $A$ yields

$$A = \begin{bmatrix} a_{11} \\ a_{21} \\ a_{31} \\ a_{12} \\ a_{22} \\ a_{32} \\ a_{13} \\ a_{23} \\ a_{33} \end{bmatrix}_{3 \times 6} = \begin{bmatrix} \frac{2}{3} (l_i' + \frac{1}{2} l_i) \cos 30^\circ & \frac{1}{3} (l_i' - l_i) \cos 30^\circ & \frac{1}{3} (l_i' + 2l_i) \cos 30^\circ & \frac{1}{3} (l_i' - l_i) \cos 30^\circ & \frac{1}{3} (l_i' - l_i) \cos 30^\circ & \frac{1}{3} (l_i' + 2l_i) \cos 30^\circ \\
\frac{1}{2} l_i & \frac{1}{2} l_i & \frac{1}{2} l_i & \frac{1}{2} l_i & \frac{1}{2} l_i & \frac{1}{2} l_i
\end{bmatrix}$$  \hspace{1cm} (1)

In homogeneous coordinates form, $A$ yields

$$A = \begin{bmatrix} a_{11} \\ a_{21} \\ a_{31} \\ a_{12} \\ a_{22} \\ a_{32} \\ a_{13} \\ a_{23} \end{bmatrix}_{3 \times 6} = \begin{bmatrix} a_{11} \\ a_{21} \\ a_{31} \end{bmatrix}_{6 \times 6}$$  \hspace{1cm} (2)

When the upper platform moves, $A$ changes in the static coordinate. Let $G$ be the coordinate vector of the upper hinge points, then $G$ yields

$$G = \begin{bmatrix} g_{11} \\ g_{21} \\ g_{31} \end{bmatrix}_{6 \times 6} = T \cdot A$$  \hspace{1cm} (3)

where $T$ is the transformation matrix from the moving coordinate system to the static coordinate system, and

$$T = \begin{bmatrix} \cos \beta \cos \gamma & -\cos \alpha \sin \gamma & \sin \alpha \sin \gamma & \sin \alpha \cos \gamma & \cos \alpha \cos \gamma & X \\
\cos \beta \sin \gamma & \cos \alpha \sin \gamma & \sin \alpha \sin \gamma & \sin \alpha \cos \gamma & \cos \alpha \cos \gamma & Y \\
\cos \beta & \sin \beta & \cos \beta & \sin \beta & \cos \beta & Z \\
0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}.$$  \hspace{1cm} (4)

Let $B$ be the coordinate vector of the lower hinge points $B_i (i=1, 2, \ldots, 6)$. The three elements at the first row, second row and third row of the first column are the coordinates of X axis, Y axis and Z axis in the static coordinate system. Then $B$ yields

\[ \begin{align*}
A & = \begin{bmatrix} a_{11} \\ a_{21} \\ a_{31} \\ a_{12} \\ a_{22} \\ a_{32} \\ a_{13} \\ a_{23} \\ a_{33} \end{bmatrix}_{3 \times 6} = \begin{bmatrix} \frac{2}{3} (l_i' + \frac{1}{2} l_i) \cos 30^\circ & \frac{1}{3} (l_i' - l_i) \cos 30^\circ & \frac{1}{3} (l_i' + 2l_i) \cos 30^\circ & \frac{1}{3} (l_i' - l_i) \cos 30^\circ & \frac{1}{3} (l_i' - l_i) \cos 30^\circ & \frac{1}{3} (l_i' + 2l_i) \cos 30^\circ \\
\frac{1}{2} l_i & \frac{1}{2} l_i & \frac{1}{2} l_i & \frac{1}{2} l_i & \frac{1}{2} l_i & \frac{1}{2} l_i
\end{bmatrix}_{3 \times 6} \\
B & = \begin{bmatrix} b_{11} \end{bmatrix}_{6 \times 6} = \begin{bmatrix} a_{11} \\ a_{21} \\ a_{31} \\ a_{12} \\ a_{22} \\ a_{32} \\ a_{13} \\ a_{23} \end{bmatrix}_{6 \times 6} = \begin{bmatrix} a_{11} \\ a_{21} \\ a_{31} \end{bmatrix}_{6 \times 6} \\
G & = \begin{bmatrix} g_{11} \\ g_{21} \\ g_{31} \end{bmatrix}_{6 \times 6} = T \cdot A
\end{align*} \]
In homogeneous coordinates form, $B$ yields

$$B = \left[ \begin{array}{c} \frac{1}{3} (l_i + \frac{1}{2}l_i') \cos 30^\circ \frac{1}{3} (l_i - l_i') \cos 30^\circ \frac{2}{3} (l_i + \frac{1}{2}l_i') \cos 30^\circ \frac{1}{3} (l_i - l_i') \cos 30^\circ \frac{1}{3} (l_i + \frac{1}{2}l_i') \cos 30^\circ \frac{1}{3} (l_i - l_i') \cos 30^\circ \\
\frac{1}{2} l_i' \quad \frac{1}{2} l_i + l_i' \quad \frac{1}{2} l_i' \quad \frac{1}{2} l_i \quad \frac{1}{2} l_i + l_i' \quad \frac{1}{2} l_i' \end{array} \right]$$

(5)

Let the coordinate of $O'$ in the moving platform be $[0 \ 0 \ 0 \ 1]^T$. The displacement of the six rods can be obtained by the distance between the six upper hinge points and the corresponding lower hinge points subtracting the initial length of six hydraulic cylinders. The distances between the upper hinge points and the lower hinge points are

$$d_i = \sqrt{\sum_{j=1}^{6} (g_j - b_j)^2} \quad (i = 1, 2, \ldots, 6).$$

(7)

The displacements of the rods yield

$$\Delta d_i = d_i - l_i \quad (i = 1, 2, \ldots, 6).$$

(8)

3. **Embedded control system**

3.1 **Hardware design**

3.1.1 **Analog input module**

Analog input module includes signal conditioning circuit and analog-to-digital conversion circuit. The analog input signal conditioning circuit is utilized to convert the 4-20mA that the displacements sensor output to 0-10V analog voltage signal. Analog input signal conditioning circuit mainly consists of two parts, i.e., a reference voltage circuit and a signal conversion circuit. Therefore, chip AD7606 is utilized to convert analog signals into digital signals.

The 5V voltage inputted is filtered the high frequency interference signal by a filter circuit consisting of an inductance (L2) and a capacitor (C23) and reduced to 2V by a chip REF3220. The following circuit is designed to reduce the resistance. The reverse circuit will only change the polarity of the reference voltage. The power supply circuit includes the positive +5V power.

AI is the 4-20mA analog current signal that will be converted to 1-5V analog voltage signal (Vin) by two resistors R14 and R15. The two order circuit is utilized to filter high frequency interference signal from the pre-circuit.

3.1.2 **Analog output module**

In order to increase the drive ability of the ±10V analog signal that the chip DAC7728 outputs, the analog signal conditioning circuit, which can convert the low driving ability ±10V analog signal into high drive ability ±10V or ±40mA analog signal, is designed.

3.2 **Software design**

3.2.1 **Analog input**

There are 8 analog input channels from V0 to V7 in AD7606. The former four channels and the latter four channels are controlled by two pins CONVST_A and CONVST_B of AD7606 respectively. Six analog input channels are utilized in this paper, therefore, they are paralleled into one signal AD7606_CONVST, which is connected to pin PWM of STM32.
A pulse with more than 50ns duration, which will reset AD7606, is inputted into pin RESET, and then a low level pulse with more than 25ns duration is inputted into CONVST, consequently, the analog converting will be started. When the converting is accomplished, pin BUSY will become low level and output a falling edge, and then the data can be read. The two pins CS and RD, i.e., NE4 and NOE, control the analog converting and data reading. When pin NE4 produces a falling edge with more than 0ns duration, pin NOE will produce a falling edge, and then the data will be read. The low level of pin NOE should have more than 21ns, and the high level should have more than 15ns.

### 3.2.2 Analog output

The timing sequence is used to correct the configuration of the data input registers of the DAC7728 when the correction engine is closed and the DAC outputs are updated in the synchronization mode. Set R/W to a low level and hold at least 2ns, and then CS produce a falling edge, the data will be written into DAC7728 register, CS holds a low level at least 25ns and then becomes the high level, and holds not less than 2ns, R/W becomes high level. The data writing has been completed, but the analogs of DAC7728 haven’t been outputted. Pin CS produces a rising edge after at least 5ns, LDAC produces a falling edge, and holds not less than 10ns, then turn to the high level, and then the analog output is completed. The writing operation mode is used to the writings of configuration register, shift register, monitor register and general purpose input output (GPIO) register. The data writing is controlled by pin NE3 and pin NEW of STM32. Pin NE3 should hold not less than 25ns and R/W should hold not less than 29ns.

### 3.2.3 Software design of controller

Controller software is established based on μC/OS-III. The μC/OS-III, which can be upgraded and solidified and don’t limit the number of tasks, is a powerful real-time kernel based on priority. As a third-generation system kernel, μC/OS-III supports most of the functions that modern real-time kernel needs, such as resource management, synchronization, communication between tasks and so on. However, some special functions that μC/OS-III supports cannot be supported in other kernels, such as complete measurement of the running time, directly sending signals or messages to tasks, function that tasks can wait for multi kernel targets at the same time and so on. The system framework of controller software is divided into hardware layer, intermediate layer, software layer and function layer. Function layer mainly includes Ethernet polling, electro-hydraulic servo control, inverse kinematics, trajectory planning and data sending task. Table 3 shows the system framework of controller software.

| Function layer | Ethernet polling | Electro-hydraulic servo control |
|----------------|-------------------|---------------------------------|
| Software layer | Ethernet protocol stack LwIP |                                |
| Intermediate layer | Ethernet driver | AD7606 driver                  |
| Hardware layer | Ethernet | Displacement sensors |
| Inverse kinematics | Trajectory planning | Data sending |
| Real-time operating system μC/OS-III | | |
| DAC7728 driver | I/O | |
| servo valves | Button, Switch valve | |
The embedded control system is divided into five tasks. In order to ensure the real-time performance of the electro-hydraulic servo control system, PID position closed-loop mission of multichannel electro-hydraulic servo control system should have the highest priority. Ethernet polling and receiving function is used to real-time receive the instructions sent by the upper computer to ensure the smooth control. It should be the second highest priority. The rest of the tasks should be set to lower priority. Table 4 shows the corresponding function name, priority partition and function of each task in the system.

**Table 4. Configuration of task priority and function introduction**

| Task name                  | Function name     |
|---------------------------|-------------------|
| Electro-hydraulic Servo control | Servo             |
| Ethernet polling          | Start             |
| Inverse kinematics         | Solver            |
| Trajectory planning       | Trace             |
| Data sending               | Eth               |
| Priority                  | Function          |
| 1                         | PID position closed-loop control |
| 2                         | Ethernet polling and receiving program |
| 3                         | Kinematics inverse program of SEMP |
| 4                         | Trajectory planning of SEMP |
| 5                         | Data packaged and sent via Ethernet |
4. Experimental verification of SEMP

4.1 Experimental system of SEMP

The rigid body of SEMP has been shown in Fig. 1. Fig. 4 shows the electrical connection diagram of the control unit of SEMP. Hardware of control unit mainly concludes the following parts: the controller of motion platform, analog input signal conditioning board, analog output signal conditioning board and power supply.

Fig. 4. The electrical connection diagram

The experiment system of SEMP is mainly composed of two parts: mechanical and hydraulic unit, and embedded control unit. Fig. 5 shows the overall structure of the control system of SEMP. The pump station provides hydraulic power for this motion platform. Six-channel hydraulic locks controlled by digital data allocate oil source into six ways by diverter valve block to each hydraulic cylinder of the platform. The displacement signals of the 6 built-in displacement sensors installed on the electro hydraulic motion platform are collected and the six electro-hydraulic servo valves are driven by the system. Real time control is realized by controller software and real time monitoring and parameter configuration of the control system are realized by the human-computer interaction interface.

Fig. 5. General diagram of the control system of SEMP

4.2 System experiments of SEMP

After verifying the feasibility of each channel, this paper carries out system experiment for the motion platform. The following characteristics of six hydraulic cylinders are tested. Physical sports figure of SEMP is shown in Fig. 6.
Firstly, the translational test of the upper platform along the X axis is carried out. A sine signal with amplitude of 2.5mm and a frequency of 2Hz is given. The experiment curve of the sine signal tracking is as shown in Fig. 7. In this paper, the translational and rotational motions along the other axes are also carried out.
Fig. 7. Curves of X-axis shift wave tracking experiment
A sine signal with amplitude of 4° and a frequency of 2Hz rotating around the X axis is given. The experiment curve of the sine signal tracking is as shown in Fig. 8.

Fig. 8. Curves of X-axis rotate wave tracking experiment
Through the experimental verification, the embedded control system can effectively complete six hydraulic cylinders position servo closed-loop control. Its tracking performance is very good.

5. Conclusions
This paper designed a SEMP and the parameters of SEMP are shown. A novel embedded control system for SEMP is obtained through hardware and software co-design. Compared with controllers based on PC, the embedded control system designed has obvious advantages of low cost and power consumption, small volume and convenience. The performance of the embedded control system is verified. This control system has good interactivity, flexibility, expansibility and good performance.

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