The Design of Inverted Pendulum System Based on Virtual Prototype Technology and PID Control

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***Abstract*—A design scheme of a single Inverted Pendulum Virtual Prototype based on the combination of software and hardware is introduced. It uses hardware platform of C8051F020 single chip and the software of Matlab, Visual Basic and Kingview. It can simulate the force and movement of Inverted Pendulum expediently and intuitively. The combination of software and hardware makes the system closer to the reality. The concrete scheme is introduced in the paper and the result of PID control which verifies the correctness of the scheme.**

***Keywords*-inverted pendulum; virtual prototype; PID**

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1 Introduction

As an absolute unstable system, Inverted Pendulum is always a hot topic in the control area. It has the feature of high order, multivariable, nonlinear and strong coupling. The Inverted Pendulum is widely used in aviation, robots, mandrills in acrobatics and the study of control theory. It has important value of theory and practice in the automation area [1].

In the simulation study area of Inverted Pendulum, most methods are from the perspective of mathematic model. And a large amount of assumptions that always ignore many key factors of the system are made in the design process. Therefore the simulation results can not reflect the real appearance. The Virtual Prototype Technology uses computer to build the mathematic model of the mechanical system to do the simulation analysis and it shows all kinds of feature by the way of graphic in the real engineering specifications. Based on the above reasons, Virtual Prototype Technology can be used to overcome the defects of the mathematic model simulation [2]. In this paper, the scheme used software and hardware to simulate the Inverted Pendulum based on Virtual Prototype Technology is introduced. The use of hardware makes the simulation closer the reality. This scheme can do visual simulation on function, feature, force and movement. And PID algorithm is used to control the system.

2 Inverted pendulum model

The elementary diagram of the single Inverted Pendulum is shown in the Fig. 1.

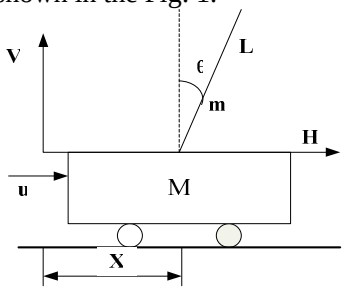

Figure 1. Elementary diagram of Inverted Pendulum

In the figure, M is the quality of the car. m is the quality of the pendulum. x is the displacement of the car. θ represents the pendulum angle, u is the input as control data. L represents the length of the pendulum. l is the gravity arm of force that equals a half of the L . V represents vertical direction while H represents horizontal direction.

The control target of the system is to generate appropriate u which make the system recover balance state （$\theta = 0, x = 0$） under certain initial condition. According to the Newton's law, the horizontal and vertical direction state equation is built, and then the intermediate variable is eliminated, and linear processing is done that makes $\sin\theta = \theta$, $\cos\theta = 1$ in the balance sate. So the state equation is got [3].

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases}, \qquad (1)$$

In the equation (1),

$$x = \begin{bmatrix} \theta & \dot{\theta} & x & \dot{x} \end{bmatrix}^T,$$

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$$A=\begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{m(M+m)gl}{(M+m)I+Mml^2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{m^2gl^2}{(M+m)I+Mml^2} & 0 & 0 & 0 \end{bmatrix},$$

$$B=\begin{bmatrix} 0 \\ -\frac{ml}{(M+m)I+Mml^2} \\ 0 \\ \frac{I+ml^2}{(M+m)I+Mml^2} \end{bmatrix},$$

$$C=\begin{bmatrix}0 & 0 & 1 & 0\end{bmatrix},$$

$$D=0.$$

3 System design

The scheme mainly consists of the hardware circuit and the software design.

3.1 Structure of System

The system mainly is consist of there parts. There are Controller, Virtual Inverted Pendulum and Host Computer. The structure of the system is shown in the Fig. 2.

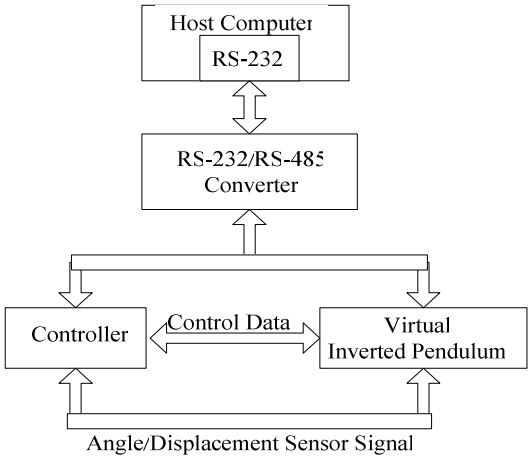

Figure 2. Framework of the system

The Controller and the Virtual Inverted Pendulum both use the same hardware platform which designed by C8051F020 single chip. The Controller collects the angle and displacement signal and runs the PID algorithm to output. In the Virtual Inverted Pendulum, the hardware is used as a virtual load to get control data from the controller and output the sensor signal and communicate with the host computer to get the real angle and displacement result. The host computer executes simulation algorithm to work out the real-time state of the Inverted Pendulum and shows the cartoon interface and all parameters. The RS-232/RS-485 converter is used as a bridge of communication.

3.2 Hardware Circuit Design

The hardware mainly completes the input and output of analog signal and digital signal, key, LCD and communication. The C8051F020 single chip is a high performance designed by Silicon labs. It has line command structure, 12 bits successive approximant A/D converter, 8 analog channels and two 12 bits D/A converters [4]. The structure framework is shown Figure 3.

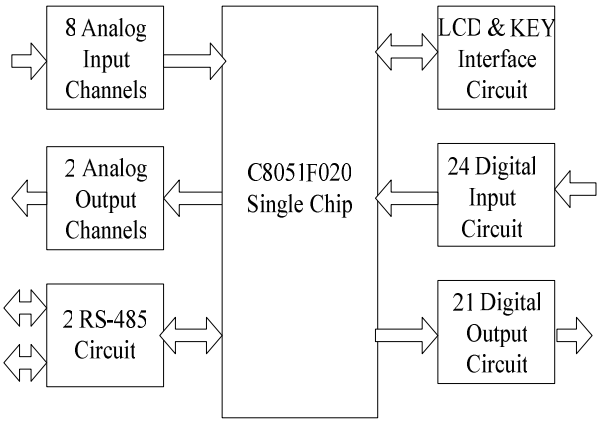

Figure 3. Framework of hardware circuit

The Virtual Inverted Pendulum uses the hardware platform to accept the control signal by Analog Channel Input from the controller and send the sensor signal to controller through the Analog Output Circuit. It transforms the real value of the angle and displacement that are from the host computer to the sensor signal of 4-20mA current of the real sensor output by the D/A converter, then output the current through analog output circuits. At the same time, it gets the control data through analog input channels circuits and transforms the control signal to 0-4096 digital data and transfers to the host computer. It is used as a virtual load to achieve the data transform and communication. The data transform makes the mathematic model data same to the real physical.

3.3 Software Design

The software mainly achieves to build the Inverted Pendulum mathematic model and show the system state by the way of cartoon. On the host computer, these function is achieve by used Matlab, VB and Kingview. The framework is shown in the Fig. 4.

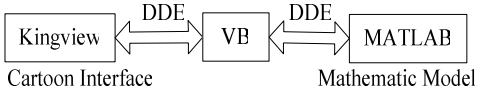

Figure 4. Framework of software

From the above equation （1）, we can see that the mathematic model contains matrix, integral and differential operation. It is very complicated. Matlab is a kind of software that has strong operation function. So we use Matlab to build the mathematic model. The Kingview is a kind of strong industrial software. It can achieve complex and interactive man-machine interface. VB as a bridge between Matlab and Kingview is to transfer data and communicate to the hardware. It transfers the control signal to the mathematic model and sends the mathematic result to the cartoon interface to show. They communicate through DDE (Dynamic Data Exchange) protocol.

The DDE communication between VB and Matlab

On the condition of Windows, DDE is an effective method of exchange real-time data during different application program. It is a protocol of share data during different application program. In this design, the Matlab and Kingview application program is the client program while the VB application program is server program [5].

The DDE communication software is designed on the Simulink of Matlab. It uses S-Functions that exist in the way of M-file to achieve. The DDE simulation framework is shown in the Fig. 5.

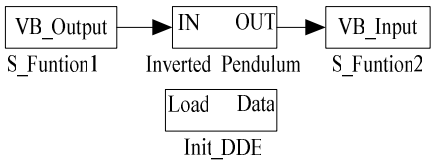

Figure 5. Framework of DDE communication

The Matlab application program transfers the pendulum angle, pendulum angle rate, pendulum angle acceleration, car displacement, car rate and car acceleration to the VB application program while VB application program transfers the control signal to the Matlab application program.

The design of the Virtual Prototype interface

The cartoon interface application program uses Kingview of Version 6.5.3 to do the secondary development. The interface designed on the Kingview can shorten the development cycle greatly. Then the interface is run on the TOUCHVIEW of the Kingview，it can shows the change of the dynamic data through the cartoon. And it can achieve to monitor function of history data recording and trend curve etc. The interface is shown in the Fig. 6.

In the interface, we can see the Inverted Pendulum movement with the pendulum angle and car displacement change. And all the parameters are also shown. We can also see the change curve of the angle, displacement and the force.

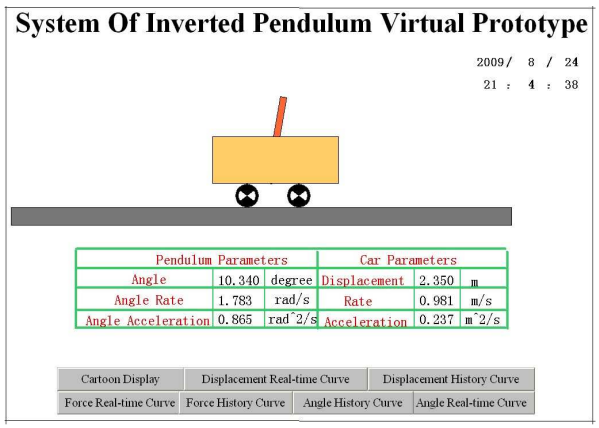

Figure 6. Interface of Inverted Pendulum Virtual Prototype

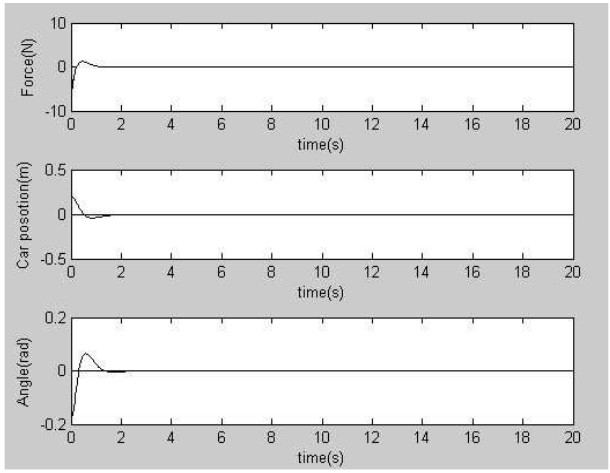

Figure 7. The result of PID control

4 Pid control scheme

The PID controller uses the control data that is got through the linear combination of the proportion, integral, derivative of the deviation to control the objects. The PID algorithm is a common control method in the production process. The PID control principle framework of the Single Inverted Pendulum is shown in the Fig. 7.

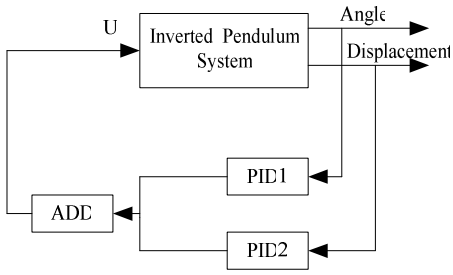

Figure 8. Principle framework of PID control

From the framework, it can be seen that double-loop PID control is used. The goal of control is to make the pendulum angle and car displacement to zero. The digital place PID algorithm is used to control the system. The algorithm equation is shown below.

$$u(k) = k_p * error(k) + k_i * \sum_{j=0}^{k} error(j) * T + k_d * \frac{error(k) - error(k-1)}{T} \quad (2)$$

In the equation (2), T is sample period, $error(k), error(k-1)$ are respectively the deviation at the time of k and $k-1$[6].

The integral term makes system overshoot. Because of the system is a very unstable system, the angle and displacement are must in a certain range, or it will have the phenomenon of 'knock off wall'. So k_i equals to zero. The PID control result is shown in the Fig. 8.

From the figure, it is known that using the PID control can make the system to balance state in short time. And it proves that the virtual system is correct. Because the control is very rapid, we can set time scaling factor that change the system running period to watch on the cartoon interface.

5 Conclusion

The design scheme of software and hardware co-design is used to make the virtual system that is designed more practical. The virtual system can simulate the movement and force of the real inverted pendulum. The design with low cost is convenient and can be used in experiments and industrial scene.

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(From P.45)

\\ Local\ Move vertically 1=\\ Local\Move vertically 1-1;
If (\\ Local\Move vertically 1==0&&\\ Local\Block moves vertically2==100)
\\ Local\Implied symbol =0

6 Conclusion

The character of this automatic control system of Robots is that its control of physical object layer is taken small scaled S7-200 PLC, which is more flexible, accurate, easy to mend and extend. Host computer monitoring software is taken Kingview to develop configuration software, which is user friendly interface, high automation and reliable monitor[4].Furthermore, the development of this Robots control system is meaningful to the transportation of industrial on-site cargoes.

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