Network Remote Closed-loop Control Based on Virtual Reality

Su Xiao-hui, Ge Yu-zhou, and Xu Shu-ping
Computer Science and Engineering College, Xi'an Technological University Xi'an 710032, China
E-mail: drxushuping@yeah.net

***Abstract*—Aiming at the issues of random delay and delay uncertainty in the control information network, a kind of network remote closed-loop control structure based on virtual reality is proposed. In accordance with the idea of open-loop system to achieve closed-loop control, this method focuses on constructing the virtual controlled object model in the client, making the virtual simulation system and the actual operation of the system state similar or even identical, and allowing the operator to decide the next control instruction which is according to the operation of the virtual simulation system at the same time. By this means, the required control instructions to the actual system is given accurately, which makes purpose of remote real-time control possible. Simulation results show that the structure of the remote control system obtains good dynamic quality and reduce the impact of network delay aspects to the system dynamics characteristics, which is a reference idea to the remote real-time closed-loop control.**

***Index Terms*—Virtual Reality; Network Time-delay; Remote Control; Closed-loop Control; Simulation**

I. Introduction

The network control system is the extension of the control distance, and the long-distance transmission of control signals will inevitably bring about the delay of the signal [1]. Remote control system, with Internet based on TCP/IP protocol as a means of information transfer, can make control equipment connected to any node within the Internet at any time, any place [2]. Remote control system based on control information network actually is pulled away by the both ends of control system, between the controller and the controlled object across a computer network to do the information transmission, but in such a system, the basic requirements of the control system has not changed, and increased the difficulty of control [3]. The experiments show that the larger delay produced a certain time delay and uncertainty during transfer in the Internet information, which would make the entire system's control quality seriously deteriorate, and it's a bottle neck problem of impact the development of remote control technology based on Internet [4].

In order to relief the impact of network latency on system performance, we must find new control concepts from the basic principles of the control system. The literature [5] is according to the principle of packet transmission of the TCP/IP protocol, using stochastic process theory from the macroscopic research on statistical characteristics of time delay, and on the basis of two kinds of prediction algorithm. It adopts the method of stochastic process theory that study time delay variables is worth reference, but the volatile prediction error, may lead to system instability and so on. The robot network control method based on event driven is put forward in the literature [6], the operator sends target instruction, through remote robot behavior planning run continuously to the target state, this method can avoid delay variation problem. According to the linearization method for robot, using Smith prediction control constant delay problems in the literature [7], this method, in the application of network delay changes in the environment, has the certain difficulty, often cause system unstable situation. The delay time predictor based on RBF neural network is proposed in the literature [8], delay time on the local control terminal for Smith to estimate the parameters of the real-time correction and solve the stability of the variable time delay case Internet robot system. Based on the literature [9], which reduce the remote control system block diagram of the Internet make the forward delay and feedback delay into total delay, this system only need to design a compensator, simplified system design, and uses the Smith compensator to compensate control, improving the quality of the system. For the uncertainty of network time delay, control in the field of computer used buffer technology, converting the uncertain time delay to the fixed time delay, even not for network time delay prediction, also can achieve good control effect. The hydraulic system is used as the controlled object in the literature [10], and the challenging research of the remote control system under the Internet environment is put forward. The experimental results show that when the principle of Smith compensator and the appropriate time delay prediction algorithm are adopted to design the dynamic compensator, it can make delay link, which dose not to join the network, stable before the original system, and restore stability after joining the network, which makes use of the Internet mechanical movement to make the remote control possible. But because of the uncertainty of the network transmission delay and the sampling information processor datagram using strategy of deformation in the transmission of control signal, it makes the system steady-state error. According to the current study level, there is analysis and design of the network controller by single variable to the multivariable, from sure to random, from classic control theory to intelligence

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control theory and the development of advanced control algorithm in literature [11]. But this is just the beginning, so far there is no a set of system method used to do analysis, modeling, and design the of network control system. And network architecture of the control system is also in constant change, the present method basically focuses on network time delay no more than one sampling period, and the research of other conditions remains to be further [12].

An open, interactive and realistic virtual environment created by virtual reality technology make people immersed in virtual reality to make decisions on changes in the environment based on virtual environments provided by virtual reality and to impact the virtual environment. In the "real" virtual environment, the input is a set of virtual parameters, the output is another set of virtual parameters, the two parameters linked accordance with a set relationship, the operator can respond to the input parameters timely [13-16]. Because of the good "reality" and "forward-looking", the virtual reality simulation technology is applied to the network remote control structures in this paper. According to the idea of closed-loop control in accordance with the open-loop system, a virtual operating environment is set up with the actual controlled object and its simulation model of the control parameters. The operator could conduct real-time operating to the simulation of charged objects, and at the same time the control signal that is imposed in the simulation of the controlled object is delivered to the actual controlled object through the Internet, which makes the influence of network latency exclude real-time little closed-loop control system of controlled object value. It's weak effectively the impact of network latency on the performance of the entire control system.

II. Idea of Achieve Closed-loop Control under Open-loop Condition

If the output state of the control system is only decided by its input, the control system can use a simple open-loop control to obtain an ideal control performance, which is $y = f(\mu)$, where y is the output state, μ is the input control value, such as light switches state control. However, a lot of control object has a certain complexity make the output state of the system can not be uniquely determined by the control value and with the current state of the system, which is the relationship of the system output y and input μ can be written as $y = f(x, \mu)$, which requires that the system is observable because of control value to determine the current state for system need. Yet under the situation of interference, non-linear factors in the system, this control becomes more difficult, the input and output relationship can be written as the form of $y = \tilde{f}(x, u) + \tilde{\delta}$, which $\tilde{f}$ means time-varying of system and $\tilde{\delta}$ is the immediately interference of system. For such systems, the conventional closed-loop control is often difficult to achieve. However, control system combined with new methods is also based on the idea of closed-loop control. Closed-loop control is the desired output yr and the deviation of e of the actual output ys as the basis to adjust the control value u to control, which is $\mu = P(x, e)$, where P is the basic way to adjust the control value, such as the commonly used PID control and intelligent control algorithms. The closed-loop control, based on the designer's thinking-oriented regulation and its target, is the actual output and expected output of the system infinitely close. This is the theoretical basis of the closed-loop control with a good control performance.

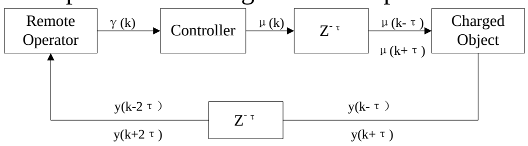


Figure 1. Internet transmission delay links in the entire system

Remote control structure based on the control information network is shown in Figure 1, the network transmission delay is an inevitable part of the system closed-loop control as $Z^{-\tau}$ shown in Figure 1.

Control instructions $\gamma(k)$ issued by the client's remote control and will obtain the output of the controller $\mu(k)$ which through the delay transmission of the Internet, time $k+\tau$ transferred to the controlled object worked for the charged object, so the time k of operator control issued instruction which actually is the last time of new control command transferred to the controller of the controlled object , that is the instruction $\gamma(k-\tau)$ issued at time $k-\tau$ produce the output $\mu(k-\tau)$; the same moment the output information $y(k-\tau)$ of the controlled object must go through the Internet latency link can transmit to the remote operation of the client, the remote operating can get the latest status information at time k is actually charged object output message $y(k-2\tau)$ at time $k-2\tau$. Thus, for remote operation of the client, at time k for the reference time, it issued instructions can be fed back to the state information after 2 times transmission delay. Therefore, the difference between the operator's command with the state of charged object is 2 τ minute delay, yet the general delay time τ can not be ignored and have the characteristics of randomness which provide higher test to closed-loop system design and system real-time requirements.

III. Three Closed-loop Remote Control Structures Based on Virtual Reality Simulation

The use of closed-loop control need some conditions as well. First, the response time of any system has a basic time constant T, which is the inherent basic attribute of system and the interval from the imposed input to the output. For implement good continuity closed-loop control to system, the input signal must be "coherent" relative to the system time constant T, for continuous systems, the control value should be applied continuously yet discrete systems need meet the requirements of the sampling theorem because of system output and system state is changing constantly, that is:

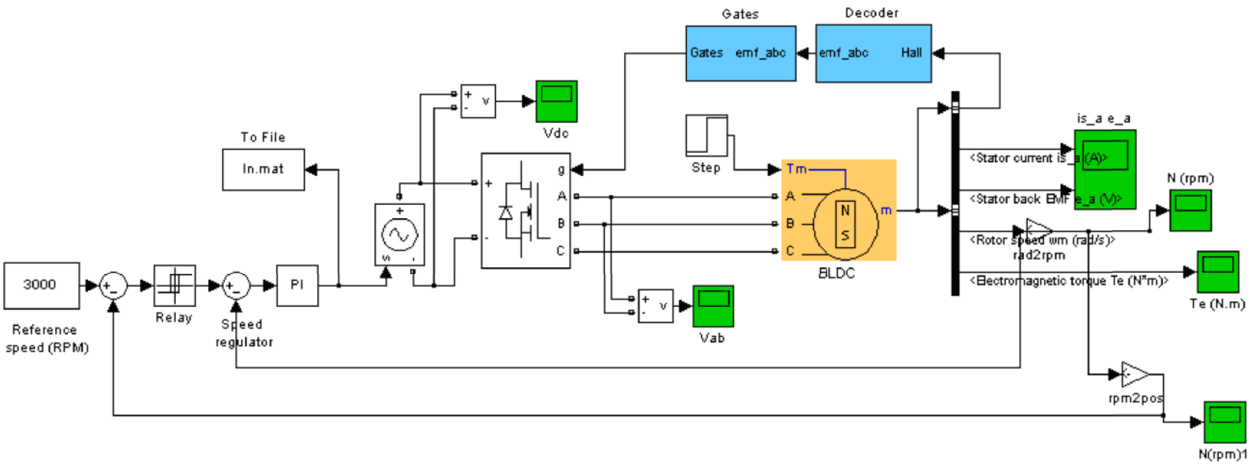


Figure 2. Closed-loop control structure of brushless DC motor

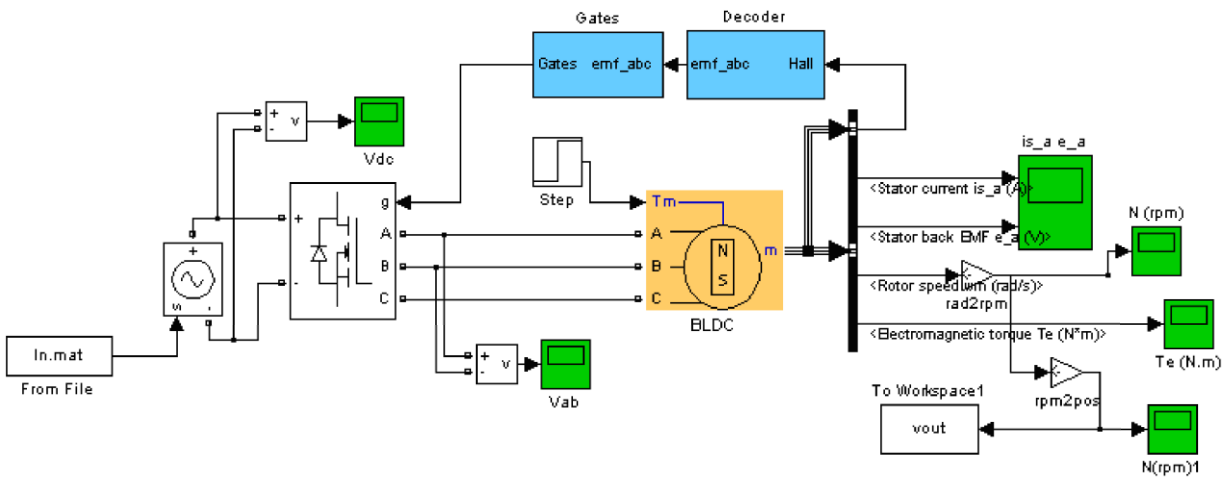


Figure 3. Open-loop control structure of brushless DC motor

$$ys(k) = f(x(k-n), x(k-n+1), ..., x(k-1), \mu(k-1))$$

where k represents the current sampling time, n represents the current output of the system related with n time domain state before the current time.

In this system actual output ys will produce error $e(k)$ with the desired output yr, then system should get the next time control $\mu(k+1)$ based on the state x and error according to certain algorithms, namely as the form (1).

$$\begin{aligned}\mu(k+1) = P(x(k-n), x(k-n+1), \\ ......, x(k-1), x(k), ys(k-1))\end{aligned} \quad (1)$$

However, network closed-loop control system with transmission delay as shown in Figure 1, due to the transmission delay of the system input and output signals, so at the same time, the formula of the output $\mu(k+1)$ at next time becomes as the form (2).

$$\begin{aligned}\mu(k+1) = P(x(k-n-2), x(k-n-1), \\ ......, x(k-3), x(k-2), ys(k-1))\end{aligned} \quad (2)$$

Obviously, (1) and (2) is different that lead to a conventional closed-loop control idea can not be applied directly to the closed-loop control system with a network transmission delay.

However, the close p control is undoubtedly the best way to solve the control problem, through analysis, the purpose of the closed-loop control system by means of closed-loop way add to the charged object control sequence $\mu(k)$ (k = 0,1,2 ......), if the control sequences can be got in advance, and then the control sequences as the input to the system directly added to the controlled object by the same timing should be able to get the same output, which is an idea of use open-loop control achieve closed-loop control effect. The so-called control is used input to get the desired output, which is the basic idea of open-loop control, input signal $\mu(t)$ control the controlled object to get output signal $y(t)$, if the charged object is a determine simple system, the output $y(t)$ can be determine by the input $\mu(t)$ only, then the control system using the open-loop control system can achieve better control performance. However, the general control system has model imprecise, time-varying characteristics, can not create a simple one-to-one relationship between the control and output, and need to monitor the control status of the controlled object, so introduction a closed loop control thought, the purpose of closed-loop control is to make the control output $y(t)$ compared with the desired output $\gamma(t)$, to adjust the controller's output value $\mu(t)$ by the difference, through a number of adjustment to get the desired output value and ultimately to achieve control. It is visible that the purpose of the closed-loop is $\mu(t)$, if the control sequence $\mu(t)$ has known through other way, then this control sequence $\mu(t)$ added to the controlled object sequentially, and the controlled object should be the same control result with the closed-loop system. This is theoretical basis of based on virtual reality technology to solve the network delay aspects impact the closed-loop control system performance.

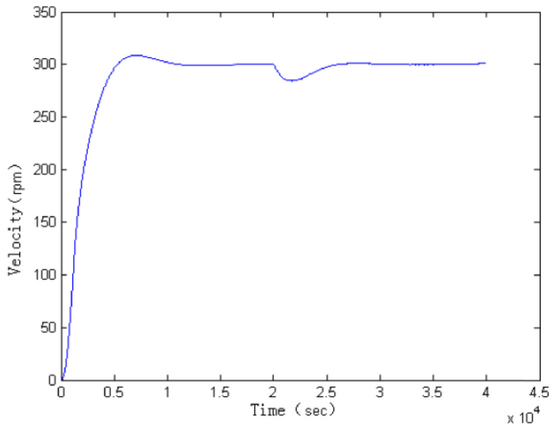


Figure 4. Open/closed loop speed curve of brushless DC motor

In order to verify this conclusion, we established brushless DC motor control block diagram shown in Figure 2 in the Matlab's Simulink environment. Simulate under the given conditions of speed 3000RPM and store PI controller output in the In.mat file, and then control sequences in the file as input sequence added to brushless DC motor control block diagram shown in Figure 3 to control open-loop. Simulation results show the speed response curve in Figure 4. The figure shows that open-loop control and closed loop control of the same control performance on the basis of known control sequences.

A. System Architecture

Transmission delay link of the network makes the time lag existed between remote operations and controlled object, there are difference between the operations can be based on parameters and needs based on the parameters resulting in the decision-making accuracy and the effectiveness of instruction. Shown in Figure 5, you can build a virtual operating environment for the remote operator by means of the actual controlled object and its control parameters of simulation model. In this environment, the simulation charged object is located in a remote client and no network transmission delay between the remote operators, the operator can real-time operation to the simulation charged objects. And at the same time the control signals $\gamma(k-1)$, $\gamma(k)$, $\gamma(k+1)$ imposed in the simulation charged objects delivery to the actual controlled object over the Internet and taken back continually the actual status information $y(k-1)$, $y(k)$, $y(k+1)$ of the controlled object, and real-time compare the state of its simulation controlled object to monitor the running state of the actual controlled object. The network delay will produce a similar delay influence for every transfer data, match the appropriate buffer technology can make to maintain continuous for data flow and make the control signal worked on the actual controlled object and taken back to the status signal to maintain a continuous to achieve real-time closed-loop control for the actual controlled object.

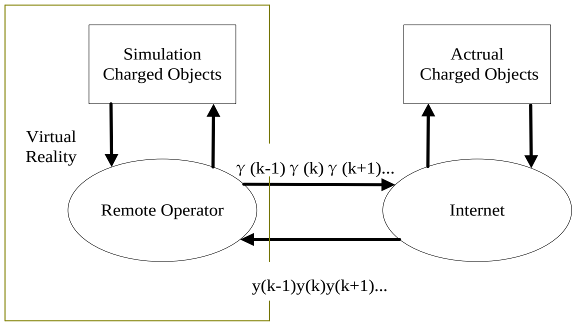


Figure 5. Virtual reality environments structural diagram

Network latency makes remote real-time control has been limited, how to "real" reflect the actual system running status by means of the system model and operators develop and implement a control command according to the "real" virtual environment is the applications target of virtual reality technology in the remote control.

B. Application Examples of Virtual Simulation Environment

In order to describe clearly the application background of virtual reality simulation, we made the application example shown in Figure 6 based on the virtual simulation environment. The left half of the figure is the remote operator to create a virtual simulation environment based on virtual reality ideas, including the display part and the control panel part, of course, this is a simple virtual reality environment, obviously, all the advantage of technology allowing operators into the reality and the technology and equipment facilitate operator to make a judgment and final operation can be used to create more complex and better functions virtual reality. The operating handle in the control panel in the figure is only a schematic which mainly used to describe a method based on virtual reality simulation environment remote control.

As shown in Figure 6, the schematic is a system for target tracking and the implementation of the fight against by a game controller in the control panel (one can shake the handle on the right control panel), the launch button (two buttons on the left control panel) and control objects in the operation display interface. First of all, the system achieve the control objects and target of virtual reality association to the actual control objects and target, that is virtual reality can be more true response to the physical environment, followed instructions in the control panel to be able to timely apply to the control object of actual environment. In the virtual simulation environment, operator consider only the running state of virtual reality, that is thought the display of the virtual simulation environment such as playing video games operation control object to track the target by game controller, then within the effective range launched the missile pursuit or shooting by launch button. When the target shoot down by players means the actual target has been shot down and task completed.

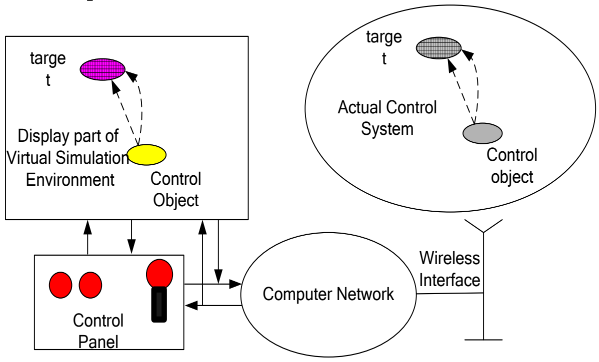


Figure 6. An application example based on virtual simulation environment

C. Three Loop-control Structure of Virtual Simulation Environment

Due to the presence of network delay on the remote control made operator dialogue to the controlled object has time delay, to meet the good characteristics of the controlled object response and real-time closed-loop control of the remote control operator ,a three closed-loop remote control system based virtual reality simulation was proposed on concept of virtual reality which control the both ends namely the operating side and charged object side to create the independent control value closed-loop structure, the dashed box shown in Figure 7 as both ends of the dumbbell structure to meet real-time closed-loop control of the actual controlled object and the virtual simulation charged object to control value; connect both ends of located at operating side and dumbbell structure of charged object as a dumbbell handle through the Internet, big closed-loop with network delay thereby to build a dumbbell-shaped three closed-loop structure. Small closed-loop at dumbbell both ends can be run independently by operators' instructions and the run command and result can be communicate with each other by middle big closed-loop-dumbbell handle to carry out a comparison of the information, interaction and updates of two little closed-loop system at dumbbells both ends. Visibility, in this structure, little closed-loop at dumbbells both ends can be run independently without network delay links, so there is a fast response speed to charged value. The dumbbell handle big closed loop with time delay links can use the actual charged object parameters at one end of the dumbbell structure according to the parameter variations of the both ends at dumbbell to modify continuously running parameters and status of virtual simulation system at the other end of dumbbell structure which make the running state of simulation system and actual system similar or even identical, while operator to virtual simulation running state of one end of system based on dumbbell structure to decide the next control instruction and judge the running state of the charged object and actual object whether identified according by running result of both ends of dumbbell structure, and judge actual system whether running normal in accordance with operating desired way. Therefore, in the three closed-loop remote control system, the operator can be give the required control instructions based on virtual simulation system and ultimately achieve the purpose of remote real-time control.

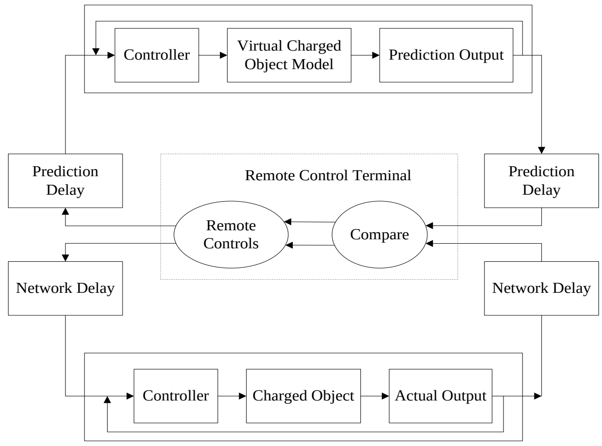


Figure 7. Dumbbell-shapes' three loop-closed structure diagram of remote control

It is obvious that the key of the system is how to create a virtual closed-loop architecture and network delay model, that is to establish a closed-loop control system of practical charged objects and their parameters, at the same time, to establish another set of the controlled object model as virtual real controlled object, then make the remote control "immersed" in the virtual reality of the controlled object model operate the controlled object model in virtual reality, while sent the operating instructions to the actual controlled object to achieve the purpose of real-time remote control the controlled object. In order to achieve the purpose of real-time control must be sent the state of the actual system into a virtual reality, so that controller can not only be implement real-time operating based on the object model in virtual reality, but also can monitor and compare the actual running state of the actual controlled object constantly to understand three closed-loop remote control system of this dumb bell-shaped whether normal running and the pace of the small closed loop at both ends of dumbbell head whether functioning properly and take the necessary measures in accordance with this result. Therefore, the key of the structure is to accurately predict network delay and accurate establish the controlled object model.

IV. VIRTUAL CHARGED OBJECT MODELING AND SIMULATION

Build a brushless DC motor remote control virtual simulation environment as shown in Figure 8 in accordance m function and simulink simulation module provided with the Matlab. The brushless DC motor model used the model provided in the Matlab standard library,

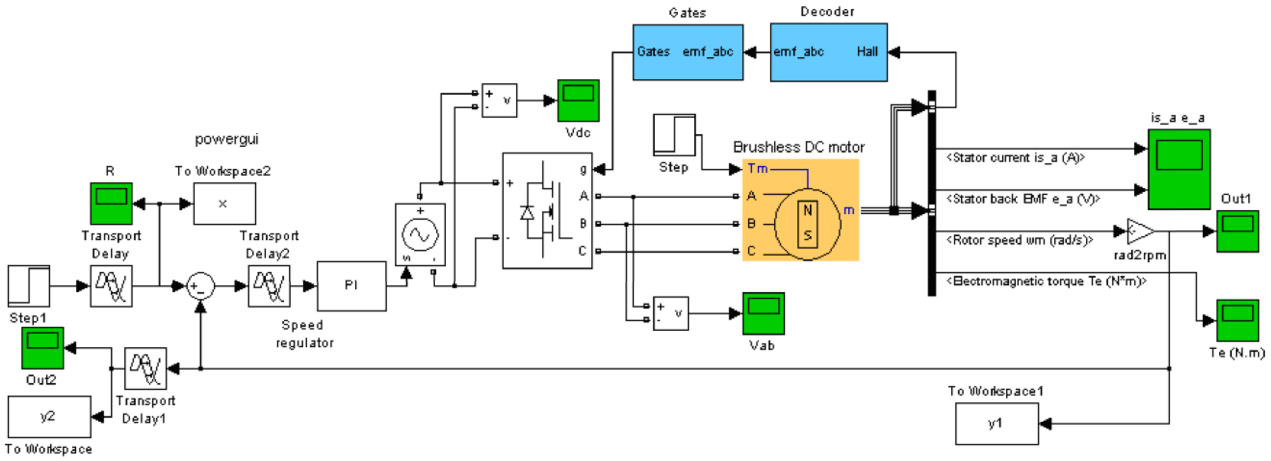


Figure 8. Schematic diagram of brushless dc motor virtual simulation system

one of the brushless DC motor due to large air gap ignored the rotor and the stator flux saturation, the magnetic flux as a linear function, and set the brushless DC motor worked in the way of two-phase conduction star-shaped three-phase six-state power supply, its mathematical model in abc phase plane such as (3) ~ (6) establish a brushless DC the motor mathematical model:

where, Ls -stator coil inductance;

Rs -stator coil resistance ;

i_a, i_b, i_c - a,b,c phase current ;

$\phi_a', \varphi_b', \varphi_c'$ - a,b,c opposite electro motive force; V_{ab}, V_{bc} -line voltage between ab and bc;

ω_γ - Rotor angular velocity;

λ - Rotor permanent magnet generated flux amplitude at the stator;

P -pole pair number;

T_e -electromagnetic torques mechanical equations:

$$\frac{d}{dt}i_a = \frac{1}{3L_s}[2V_{ab} + V_{bc} - 3R_s i_a + \lambda p\omega_\gamma(-2\varphi_b' + \varphi_c' + \varphi_c')] \quad (3)$$

$$\frac{d}{dt}i_b = \frac{1}{3L_s}[-V_{ab} + V_{bc} - 3R_s i_b + \lambda p\omega_\gamma(\varphi_a' - 2\varphi_b' + \varphi_c')] \quad (4)$$

$$\frac{d}{dt}i_c = -(\frac{d}{dt}i_a + \frac{d}{dt}i_b) \quad (5)$$

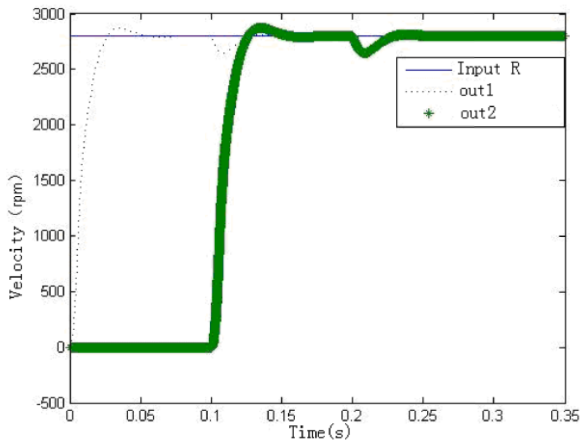
$$T_e = p\lambda(\varphi_a' \cdot i_a + \varphi_b' \cdot i_b + \varphi_c' \cdot i_c) \quad (6)$$

$$\frac{d}{dt}\omega_\gamma = \frac{1}{J}(T_e - F\omega_\gamma - T_m) \quad (7)$$

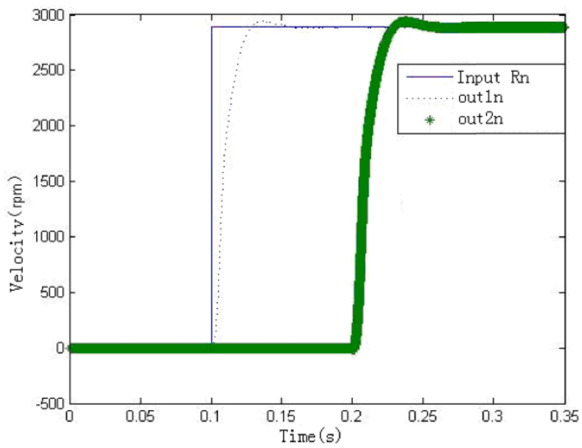
$$\frac{d\theta}{dt} = \omega_\gamma \quad (8)$$

where, J - sum of inertia of rotor and load, F - sum of viscous friction coefficient of rotor and load, T_m - mechanical torque of shaft.

Random set network delay is 0.1 seconds and set the parameters of the motor: R_s (2.8750ohm), L_s (8.5e^{-5}H), flux (0.175Wb), the top width of trapezoidal wave back-EMF (120^o), moment of inertia (0.8 e^{-5}J), friction coefficient (1 e^{-5}F), and pole number (4P). Set the network delay is 0.1 seconds, a small closed-loop delay 0.0001 seconds, at t = 0.01 seconds add a step input , and add 3 $N \bullet m$ load torque T_m when t = 0.1 seconds then simulation, the result shown in Figure 9.



(a) Response curve without delay



(b) Response curve of the input delay

Figure 9. Impact of delay links on the system input and output

To learn more about the transmission delay of network, analyze the impact of transmission delay on both ends of the dumbbell-shaped virtual simulation environment as shown in figure 7. Assume that the simulation of the controlled object and the actual controlled object is exactly the same, the same model shown in Figure 8 also on behalf of simulation controlled object and actual controlled object. And step function as input, set to a value of 0 and 0.1 seconds of delay link "Delay" and "Delay1 respectively, which Delay2 is the delay within the small closed-loop system, where is set to 0.001 seconds, you can get the results shown in Figure 9 after simulation run.

Which a diagram shows the control commands R issued from the operator (fine straight line as shown in figure) a direct work on the controlled object without delay, while the output out1 of controlled object (dotted line) is not extended and out2 (thick solid line) the delayed output. Figure b shows a control command R_n issued from the operator after delay work on the controlled object, and the output out1n of the controlled object (dotted line) is not delay and out2n (thick solid line) was delay again output. Which R , out1, represent respectively the input and output of the simulation actual controlled object; R_n , out2n represents input and output of the actual controlled object; out1 and out1n represents the artificial delay output in order to compare the simulation objects and the actual object output in Figure 9.

A diagram in Figure 9 shows speed input R of speed small closed-loop of one end of the dumbbell structure does not contain the of the network delay (thin straight line as shown in the figure), the response values out1 (dotted line) and out2 value of the response after the network delay on closed-loop transmission (thick solid line); Figure b shows the input R of speed set in the other side of the dumbbell structure after through a large closed-loop network delay (a thin straight line), and response values out1 of system work on the input (dotted line), and the out2 of the response through the network closed-loop transmission delay (thick solid line). Which the one-way network delay time is 0.1 seconds, the delay value can be set by hand in the simulation, of course, can be projection product by the radial basis function network delay model.

V. Conclusion

For the network closed-loop system of human controller as the study object combined with human characteristics as well as the requirements of network closed-loop control system, A method based on virtual reality simulation network remote closed-loop control was proposed. In this control structure, the idea of achieve closed-loop control in accordance with the open-loop system to exclude the impact of network delay on real-time closed-loop control system of the controlled object control value and no effect on the characteristics of controlled object, the charged object remote simulation system based on virtual reality simulation makes the object of fast, real-time remote control has been based, virtual reality simulation system itself constantly updated according with the actual environment changes to ensure that based on the virtual reality remote control has a certain authenticity. Simulation results show that the remote control system with this structure has good dynamic quality and reduced the impact of network delay links on the system dynamics characteristics which a reference ideas to the remote real-time closed-loop control.

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Su Xiaohui He is an associate professor in computer science and engineering college, Xi'an Technological University, China, He was born in Wugong, Shaanxi province in 1970. He has published many articles which have been indexed by EI, and his main research directions are engaged: information systems integration and information technology, database and data grid.

Ge Yuzhou was born in xi'an, China, in 1990, he is a master student in computer science and engineering college, Xi'an Technological University since September 2011, His main area of research is virtual reality applications in remote control.