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Control System Design of HVOF (High Velocity Oxygen Fuel)

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Abstract: In this paper,the High Velocity Oxygen Fuel spraying system principle and composition have been briefly introduced,and technological process of the control system has been analyzed and designed.In this paper,the HVOF spraying control system was designed and manufactured by ourselves.The hardware part is composed of programmable controller K32A3.The software part is adopted,the programmable software of Dynamic C,and the procedures are programmed.This way makes the spraying process more automatively. Especially it has carried on the analysis to the PID closed-loop control of the oxygen supply system,established the model of control system and given a realization on the procedures.

Keywords: *HVOF spraying,Programmable Controller,Automatic Control*

1. Introduction

With technology and modern industry development, people increase surface performance of various equipment components and parts. Especially the machine replacement parts which operate under heavy load, corrosive medium, high temperature, high pressure and high velocity. Materials destroy starts from component surface such as attrition, corrosion and high-temperature oxidation. Moreover, partial failure of machine replacement parts will lose effectiveness and lead equipment outage. Therefore, it is necessary to find one effective technology for improving material surface performance. High velocity oxygen fuel can achieve this target.

High velocity oxygen fuel (HVOF) is the new spraying technology based on basic flame spraying in 80s of 20th century. This is one technology that can coat on material surface with high effectiveness [1]. This method will warm up the spray materials and atomizes the grains into melting or half-melting condition. After flame acceleration of supersonic speed, the spray material will impact the formed coating or primary structure surface with high speed. Flattening material will deposit on the surface and form the high adhesive strength, density, and hardness coating [2]. In recent years, HVOF has widely application in wear resisting, anti-oxidation, corrosion resisting, and machine element repair. The past relay operation has low effectiveness in open-loop control, degree of automation and control accuracy. The main controller of closed-loop control system that based on programmable controller can realize automatic control of spray process.

2. HVOF composition, working principle and working process

2.1. System composition and working principle

Equipment combination of HVOF system includes spray gun, control panel, kerosene feed system, oxygen feed system, ignition system, water-cooling system and powder feed system. Figure 1 has the details.

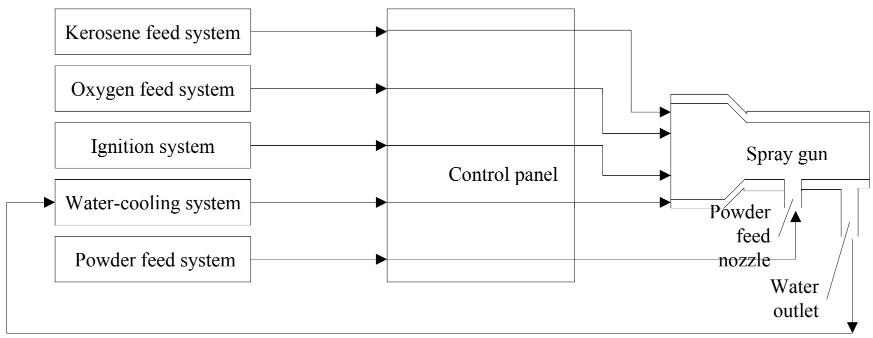

Figure 1. HVOF system constitution

HVOF process uses kerosene as the fuel and oxygen is combustion improver. Control system transforms kerosene and oxygen into spray gun under the given flow and pressure. Through high performance mixture of atomizing nozzle, the combustible mixture will spray into combustor. Then, the formed fuel gas with high temperature and pressure after spark plug ignition will add to be supersonic speed through Laval nozzle. [3] Powder feed system sends spray powder from low pressure area of Laval nozzle to supersonic jet by carrier gas. Warming acceleration from spray gun, the powder will spray on component surface as the coating. Water-cooling system will ceaseless operate water delivery through water pump for combustor cooling. Water-cooling system operates throughout the spray process for providing huge quantity of heat and damage by oxygen and kerosene burning in the spray gun.

2.2. Working process evaluation

HVOF control system is the key circle to ensure spray quantity. It has main function to automatic control the process during HVOF production. At the same time, it can adjust flame speed and temperature through fuel and oxygen control. Then it can realize spray powder warming and acceleration control. Moreover, it can realize spray parameter control for satisfying various requirements of function materials. Finally, the satisfied and simpleness spray layer can be realized under extreme condition. Evaluate the controlled system has the following process:

(1) After starting system, water pump provides circular flow for spray gun refrigeration.

(2) Control system sends oxygen with about 2.04MPa pressure into spray gun combustor. At the same time, kerosene comes out from oil pump with about 0.3-0.6MPa pressure. It will send into spray gun combustor and turns into gas through high performance atomizing nozzle.

(3) Oxygen and kerosene can mix into combustible gas in combustor. Spark plug ignition will handle this in 1 second. It will form high temperature and pressure fuel gas after burning. Then, the gas will add to supersonic speed through Laval nozzle.

(4) We use powder carrier gas send spray powder into supersonic jet through low pressure through Laval nozzle. After warming and acceleration, the powder will spray from spray gun under high speed then coat on component surface.

(5) After spraying, control system will stop providing of powder, kerosene, and oxygen, then stop cooling water supplying.

(6) Press gun clear button, the oxygen will clean mixture in the spray gun for production security. Press water clear button, powder carrier gas will clean water in cooling channels of spray gun for increase component working life.

3. Hardware system design

This control system means separately realize single control of kerosene, oxygen, powder feed pressure during spray process. Moreover, it will realize real-time monitoring about cooling water pressure, temperature, flow, and kerosene liquid level. The installed alarm system can safe system operation reliability.

3.1. Performance characteristics of programmable controller K32A3

Here we select low cost programmable controller K32A3 that based on RCM 30000 from Guangzhou Bocon Automation Technology Co., Ltd.. The CPU mode is Rabbit 3000. This is one kind of high performance equipment. It has 8 routes microprocessor that can directly manage analog quantity without analog quantity input and output model. As one kind of controller with high integration level, it has rapid data management speed. This control has 16 routes DI, 16 routes DO, 14 routes A/D, and 4 routes D/A. Moreover, it has 128K memory space, 256K bytes of user code space, and 56K bytes of FLASH storage space. User program can directly write through serials or Ethernet. It can completely satisfy performance requirement. The controller K32A3 composition frame is figure 2.

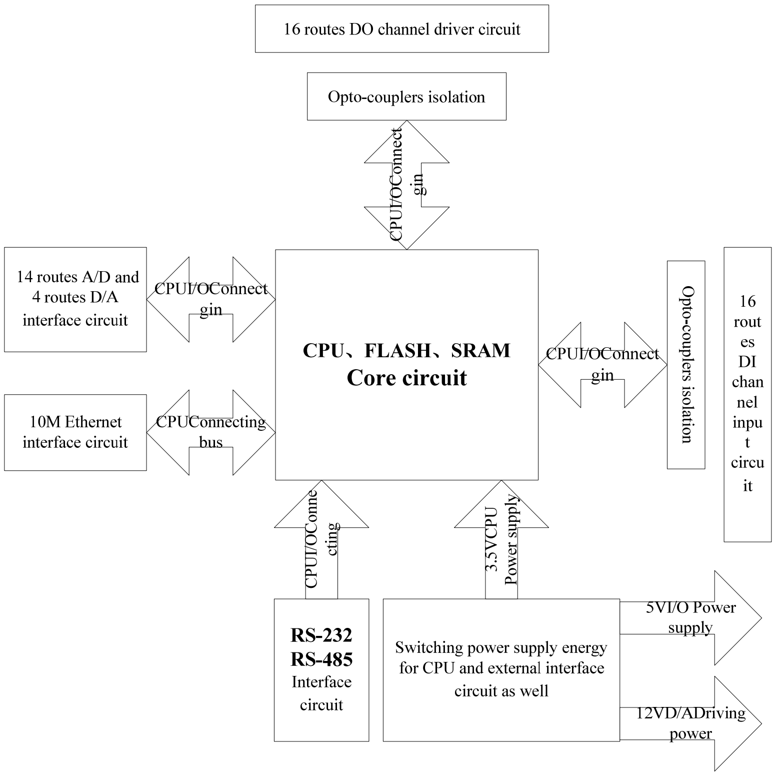

Figure 2. Constitution frame of controller K32A3

3.2. I/O integration of control system

Through evaluation of HVOF control system, here statistic this system has 7 switching value and 5 analog quantity input, 10 switching value and 1 analog quantity output. I/O point has surplus capacity for system expansion. I/O integration is in table 1.

Table 1. I/O Integration

Entrance point	Function	Output	Function
DI01	Operation button	DO01	Metering pump
DI02	Stop button	DO02	Magnetic valve 1
DI03	Powder feed button	DO03	Magnetic valve 2
DI04	Pressure sensor 3 (switching value)	DO04	Spark plug
DI05	Flow sensor (switching value)	DO05	Powder feed electrical machine
DI06	Gun clear button	DO06	Magnetic valve 5
DI07	Water clear button	DO07	Alarm 1
AD01	Liquid level sensor (analog quantity)	DO08	Alarm 2
AD02	Pressure sensor 1 (analog quantity)	DO09	Magnetic valve 3
AD03	Temperature sensor (analog quantity)	DO10	Magnetic valve 4
AD04	Pressure sensor 4 (analog quantity)	DA01	Valve 3(analog quantity)
AD05	Pressure sensor 2 (analog quantity)		

2.3. Hardware connection of control system

The hardware connection of this control system is in figure 3.

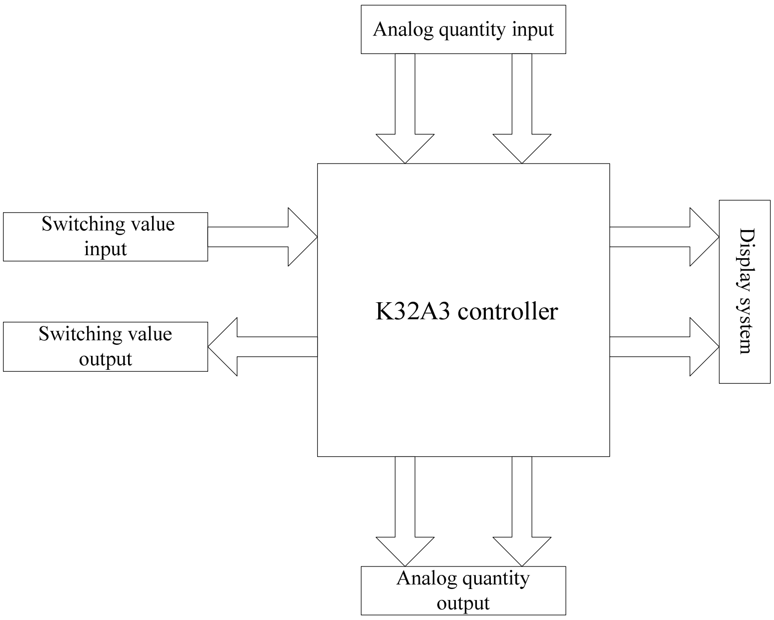

Figure 3. Hardware connection frame of control system

2.4. Display system

Display system is mainly accepting serial communication about voltage values and display current from main controller. Moreover, display them on liquid crystal display can directly express the system performance. In order to match and satisfy main controller, display system selects VTer-6448TFT-080, which stands for 640*480 pixels of LCD integration, TFT structure, and 8.0 inch. This display terminal can be controlled by color LCD of single-chip with C language programming.

Application of this intelligent display terminal needs two steps of production development. At first, connect control panel of intelligent display terminal through serials with computer. This control panel has PC serial lines, which combines RS 232 level translator chips. We can classify displayed pictures and fully use given resources on the computer for different editor, material download and stimulation adjustment. Figure 4 has the details.

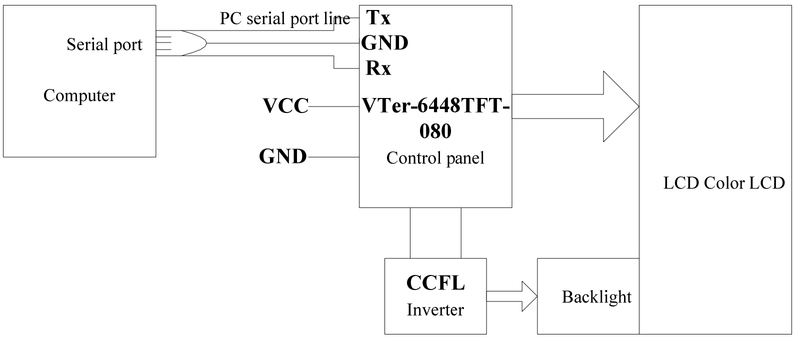

Figure 4. Connection figure between display system and PC machine

Then, separate intelligent display from computer. Through single-chip serials, intelligent display will connect with the main controller. The single-chip programming can achieve various display operations to color LCD with display commands. There has one asynchronous receiving and sending machine that named UART. Through pin Rx and Tx, it can realize asynchronous serial of full duplex communication with external circuit. We can send data from Tx, and receive data by Rx input. Figure 5 has the details.

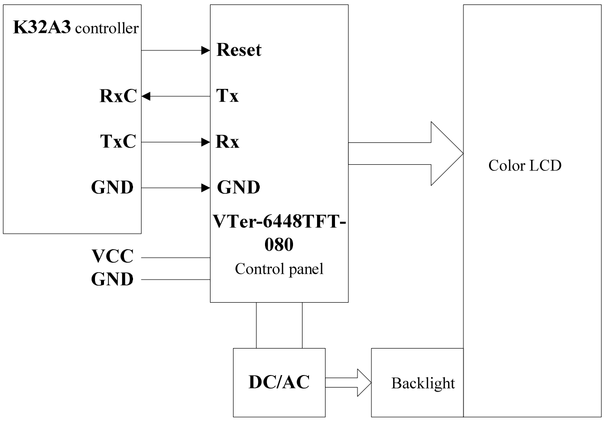

Figure 5. Serial port connection of display system and controller K32A3

4. Software system design

The main controller manages the selected voltage value and current value from various sensors through different I/O interfaces. Through adjusting circuit and reasonable control 0-10VDC voltage and 4-20mA current of corresponding algorithm output, we can control magnetic valve and proportional control valve. At the same time, it is needed to send system output parameter to display system through serial communication. This can satisfy HVOF requirement. The entire program design includes program design of main controller K32A3 and display system. The main controller program realizes essential function tasks [4]. Single-chip of display system connects with main controller through serial connection. After serial communication, the data from main controller will display on LCD for display function achievement. System serial communication has details in figure 6.

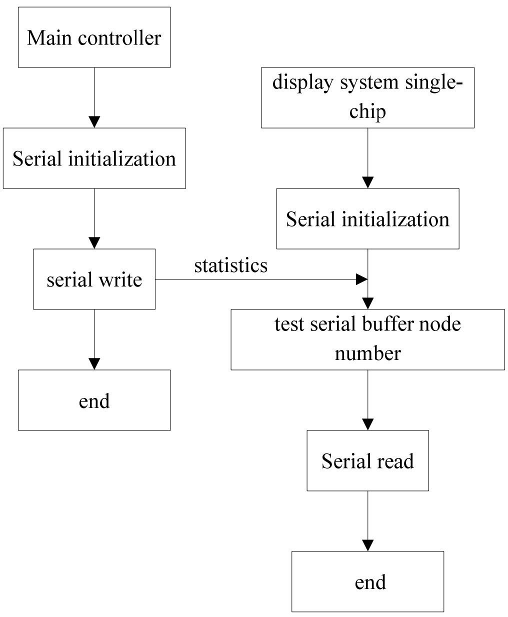

Figure 6. Process diagram of serial communication

4.1. Automatic control program of main controller

The main controller program includes system initialization, switching value input and output program, analog quantity sample management and output program, PID adjustment program, serial communication program and main program combination. The system initialization program is mainly realize controller system parameter integration initialization, build-in function references, I/O initialization, initialization setting of watchdog timer, and initialization setting of serial communication. When the switching value input pressure and the pressure is over 18VDC, the corresponding channel indicator light will turn on. This means 1. At this time, channel electrical level is high. The input voltage less than 12VDC, the indicator light will turn off, which means 0. At this time, channel electrical level is low. Switching value output of all the channels are field-effect tube output. The voltage output provides voltage for external equipment. If on channel has error, K32 will turn into protection condition. Then, STAR light will normally on. K32 will cut all the output and stop the system operation. The machine will return to normal operation until trouble removal. Analog quantity input has 1MΩ input impedance when under voltage mode. When the sampling resistance is 250Ω under current mode, we can preinstall suitable input mode based on user requirement. Moreover, we can integrate partial voltage mode and partial current mode in the channel. Analog quantity output of voltage mode is constant voltage output, and the current mode is constant current output. The constant current output has driver load of 50-300Ω. The small load needs suitable resistance for series connection. Moreover, the overall load impedance is 250-300Ω.

The main controller D32A3 has B,C,D serials. They can integrate into RS232 or RS 485 under special requirement. Here we select serial C. This serial combines with TxC, RxC and GND. They can be integrated into RS 232 electrical level[5].

Partial program of analog quantity management are in the following:

```
/*********************************************
*******************************
Function description: maintain kerosene feed pressure
between 0.3 - 0.6Mpa. It will shut down the machine and
alarm when over this range.
*********************************************
******************************/     auto int value,
channel;
    auto int i, j;
        float aiValue[4];
    while(1)
    {
       loopinit();    // Circulate initialization
          k32Run();       // K32 operation status indication and
error check
                loophead();
```

```
costate //Update AD02 quantity and DO12 quantity under pressure sensor 1 of each 10ms
    {
    aiValue[1]= anaInAmps(1); // Read AD02 quantity
    if(aiValue[1]>=10 && aiValue[1]<=15){
    digOut(11, 1); //Output alarm single 2 and control DO11 quantity
    digOut(14, 1); //Output stop button and control DO15 quantity
   }else{
    digOut(11, 0);
    digOut(14, 0);
   }
   waitfor(DelayMs(10)); //Delay 10 ms
  }

 int msBreadAI(unsigned wReg, unsigned *pwValue) //Output analog quantity
 {
 auto int no;
 #if (K32 == 'A')
     if (wReg > (AIREGNO * 2) return MS_BADADDR;
   no = wReg / 2;
     if (wReg % 2) == 0)
 A0[no].i[0] =wValue; //Output the first register data, no operation
   else
 {
 A0[no].i[0] =wValue;
     printf("AO%d=%.2f\n", no, AO[no].f);
 if(no < DACHANNELS) anaOutAmps(no, AO[no].f); //Output the second register data,operation
 }
 return 0;
 #else
     return MS_BADADDR;
 #endif
 }
```

3.2. PID accommodation

3.2.1. PID control model and mathematic application of algorithm

PID (proportion, integration, differential) control algorithm has advantages of structure simpleness, good stability, reliable operation, and convenient adjustment. We can use our own PID control for realizing closed-loop control of oxygen pressure. From oxygen feed system we can find out that proportion control valve opening has correspondence with pressure sensor output. Under the favorable environment, this correspondence is one-one mapping. Nonlinearity factor has influences to system operation. The system has to use closed-loop control. Therefore, this article establishes system model of PID close-loop control in figure 7.

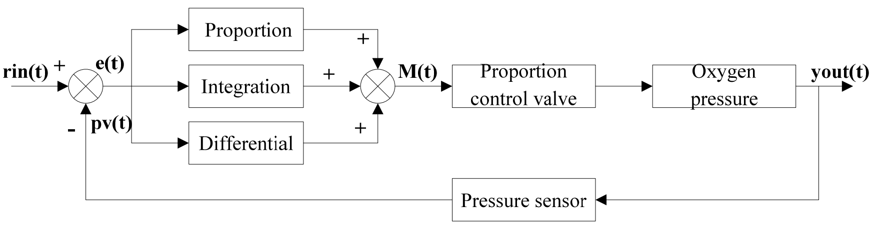

Figure 7. System design of continued closes-loop control

$$M(t) = Ke(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d \frac{de(t)}{dt} + M_0$$

(Formula 1)

In the picture: rin(t)—— set point, pv(t)—feedback point, yout(t)—system output value, e(t)—error signal.

PID control algorithm has the design that based on PID control regulation of continuous system. After digitization, the dispersed PID control planning will be written. Then, we under disperse equation for control program design. The continuous system input and output relationship is:

In formula 1: M(t) — PID controlled output; M0 —Output initial value;

e(t) — Error or error signal; K — Proportion parameter;

Ti — Integration time constant; Td — Differentiating time constant;

In formula 1, three items on the right of equal sign is proportion, integration, and differentiation part. They are the direct ratio that compare with error, error integration, and differentiation. Proportion function, integration function and differential function has the relationship. Proportion uses for regulating effect as the leading function. Integration function uses for assist regulating effect, and differential function use for compensation action. [6-7]

If the sampling period is T, the system start time is t = 0. We use rectangular integration for approximating correct integration and difference uses for approximating correct differentiation. Discretize formula 1, controller output of the n times sampling will be:

$$M_n = Ke_n + \frac{T}{T_i}\sum_{j=0}^{n} e_j + \frac{T_d}{T}(e_n - e_{n-1}) + M_0 = Ke_n + K_I \sum_{j=0}^{n} e_j + K_D(e_n - e_{n-1}) + M_0$$

(Formula 2)

In formula 2: e_{n-1} —— error value of the n-1 times' sampling;

KI—— integration coefficient;

KD—— differential coefficient.

3.2.2. PID control program

The followings are partial programs of PID control:

```
/*************************************************************************
Function description: operate PID control of oxygen pressure and maintain steady state value.
*************************************************************************/
typedef struct
{
        float SetPoint;      // Set goals
        float Proportion;    // Proportional constant
        float Integral;      //Integration constant
        float Derivative;    //Differential constant
        float LastError;     //Error 1
        float PrevError;     //Error 2
        float SumError;      // Overall error
    } PID;
PID *pp;
float PIDCalc( PID *pp, float NextPoint ) //Calculation part
    {
        float dError,Error;
            Error = pp->SetPoint - NextPoint; //Deviation
        pp->SumError += Error;         //Integration
            dError = pp->LastError - pp->PrevError; // Current integration
        pp->PrevError = pp->LastError;
        pp->LastError = Error;
            return (pp->Proportion * Error //Proportional term
            + pp->Integral * pp->SumError //Integration term
        + pp->Derivative * dError);        //Differential term
    }
……
```

4.3. Display system

Display system includes serial initialization, buffer area setting and character display. We burn the program on single-chip of display system. Through serial communication, the color LCD will display the data from main controller serial. Stimulation software window has Hex display on the lower right corner. It can automatic generate the required command of forming single-chip control. The general format is (81)+ (command code)+(color bits)+(X position coordination)+(Y position coordination)+…84. In there, 81 is communication handshaking which means command start. Command codes has two bytes, each byte has the only command code. Color bit has two bytes. The first byte is foreground color and the second one is background color. X coordination and Y coordination…… means every command has value parameter. 84 is the command epilog code, which means end. 81, command code, color bits and 84 is very necessary. The middle bytes will different which belong to the various commands. 81 and 84 is Hex. The display system program can be programed under practical requirement and individual custom. For the article length, here we no longer give unnecessary details[8-9].

In the following we will simple introduce some useful commands. The command code is Hex. Table 2 has the details.

Table2. Command function

Name	Code	Description
Display character(16X16)	4457	Display character string in the specified cursor
Display variable(8X16)	4456	Display 8X16 variable quantity in the specified position
Display bitmap	4453	Display preset FLASH bitmap in the specified start point
Clear full screen	434c	Eliminate full screen with specified background color

4. Conclusion

This system has successfully designed and applies the research into practical productions with great effect. Here we use K32A3 as the main controller, and VTer-6448TFT-080 color LCD is central program of display system. The control task achievement makes convenience of system operation. Moreover, this article uses Dynamic C as programming software. We complete control system design with C language programming and realize system requirement about software.

The writer innovation of this article is applying programmable controller K32A3 into control system of material subject. It is one typical example of interdiscipline subject. Under the background of technology generalization and industrialization, we research and design HVOF control system. This can develop our present equipment utilization efficiency and increase HVOF handle-ability and intellectuality. These points have significant meaning to HVOF equipment commercialization and application.

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