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Motion Control of Two-Wheeled Welding Mobile Robot with Seam Tracking Sensor

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ABSTRACT

This paper proposed PID controller for torch slider and PD controller for motor right wheel. to control the motion of two-wheeled welding mobile robot with seam tracking sensor touched on welding line. The motion control is realized in the view of keeping constant welding velocity and precise seam tracking even though the target welding line is on straight line or curved line. The position and direction of the body of the mobile robot are controlled by using signal errors between seam tracking sensor and body positioning sensor attached on the end of torch slider and body side of the mobile robot, respectively. In turning motion, the body and the torch slider are controlled by using the kinematic model related with two motions of body turning and torch sliding. The straight locomotion is controlled according to eleven control patterns obtained from displacements between two sensors of the seam tracking sensor and the body positioning sensor. The effectiveness is proven through the experimental results for lattice type welding line. Through the experimental results, we can see that the position value of the electrode end point and the welding velocity are controlled almost constantly both in straight and turning locomotion.

Keywords : welding mobile robot, motion control, seam tracking sensor, body positioning

Nomenclature

b : distance between driving wheel and symmetry axis
d : distance between P_o and mass center of mobile robot
D_l : coefficient of viscous friction of rotor of left wheel motor
J_l : inertia moment of rotor of left wheel motor
D_t : coefficient of viscous friction of rotor of torch slider motor
J_t : inertia moment of rotor of torch slider motor
K_{DP} : derivative gain for the mobile robot at straight motion
K_{PP} : proportional gain for the mobile robot at straight motion
K_{DS} : derivative gain for the torch slider
K_{PS} : proportional gain for the torch slider
K_{IS} : integral gain for the torch slider
K_{DT} : derivative gain for the mobile robot at turning motion
K_{PT} : proportional gain for the mobile robot at turning motion
P_c : mass center of the mobile robot with coordinates (x_c, y_c)
P_o : geometric center with coordinates (x_o, y_o), that is the intersection between symmetry and the driving wheel axis
r : radius of wheels
r_p : radius of pinion
u_s : control input for the torch slider
u_r : control input for the mobile robot
v_w : welding speed
x_o : initial distance between geometric center of mobile robot and X axis
x_s :distance of the seam tracking sensor
x_t : distance between geometric center of mobile robot and of the seam tracking end point
x_e :distance between the seam tracking sensor and P_o
l_e :distance between the body positioning sensor and P_o
$X-Y$: world coordinate system
$x-y$: coordinate system fixed on the mobile robot
m_c : mass of mobile robot excluding masses for driving wheels and rotor of motor of DC motors
m_w : mass of driving wheel including rotor of motor
I_w : inertia moment of driving wheels and rotor of motor on driving wheel axis
I_c : inertia moment of mobile robot excluding driving wheels

and rotor of motor of DC motors

I_m : inertia moment of driving wheels and rotor of motor on wheel diameter

θ_r : rotation angle of right motor

θ_l : rotation angle of left motor

θ_t : shaft angle of torch slider motor

τ_r : torque acting on the right wheel

τ_l : torque acting on the left wheel

τ_t : torque acting on the torch slider

1. Introduction

In welding process, there are many limitations for acquiring continuous and stable quality and for increasing productivity because the welding quality depends on worker's skillfulness. The welding process cannot avoid inferior circumstance such as harmful gas, dust, and strong arc light, etc. Thus, keeping manpower of welders with skillful welding ability and sustaining productivity and quality managements are very difficult. To solve the difficult problems in welding process, the automation is tried in several industrial welding fields and its adoptable range is getting broader. Specially, in the case of lattice type welding used for shipbuilding and iron structure constructing processes, the straight line part in base metal is welded using an welding carriage. However the welding for the lattice or curved part is done by manpower[2]. Especially, seam tracking sensor in automation welding system is necessary and it is divided into touch type sensor and non-touch type sensor. In case of using non-touch type sensor, there are several kinds of methods such as a method using vision system[3,4], a method using welding current sensor[5], a method using rotating arc sensor[6,7], and a method using dual-electromagnetic sensor[8]. In case of using touch type sensor, Y. B. Jeon[1] introduced a method using potentiometer to track welding seam line of lattice type in the view of theoretical approach. The non-touch type is expensive and very complex in structure. So, it is easy to be broken and contaminated by welding environment. The touch type has a simple structure, excellent endurance, low price and good application to welding field.

Y. B. Jeon[1] described its dynamic equation and motion control methods for welding velocity and seam tracking. The proposed control methods were proved through simulation results, but it could not show those practical effectiveness. In this paper, the motion control of two-wheeled welding mobile robot based on experimental results are shown and the hardware composition developed for realization of practical control is described. The controller for the mobile robot is developed by using 16 bits microprocessor of Intel 80c196kc and the motion control is realized in the view of keeping constant welding velocity and precise seam tracking even though the target welding line is on straight line or curved line.

The robot is composed of microprocessor based controller, two driving wheels, torch slider and seam tracking touch sensor etc. The two driving wheels and the torch slider are controlled by DC motors with feedback of velocity measured by encoder interrupt sensor. The position and direction of the body of the mobile robot are controlled by using signal errors between two potentiometer types of touched sensors attached on torch slider and body positioning sensor. In turning motion, the body and the torch slider are controlled by the kinematic model related with two motions of body turning and torch sliding. The straight locomotion is controlled according to eleven control patterns obtained from displacements between seam tracking sensor and body positioning sensor. The effectiveness is proven through the experimental results for lattice type welding line.

2. Composition of Welding Mobile Robot

2.1 Design of welding mobile robot

Photo. 1 shows the developed welding mobile robot. Fig. 1 shows the configuration of the developed welding mobile robot. The robot is composed of main controller part, driving actuator part, body and seam tracking sensors. The main controller is developed by using Intel 80c196kc microprocessor and it is composed of main CPU, motor drivers for locomotion control, keypad for input of welding conditions and 7-segment displaying those values. The driving actuator part is composed of two wheels connected with bevel gear to DC motor(24V, 24W). Not only to obtain the dragging power to mobile the robot with a specified velocity in spite of the weighted welding torch cable but also to remove easily the iron pieces and fragments attached under the electromagnet bottom, an electromagnet is attached to the center of the body.

Photo 1 Photograph of the developed welding mobile robot

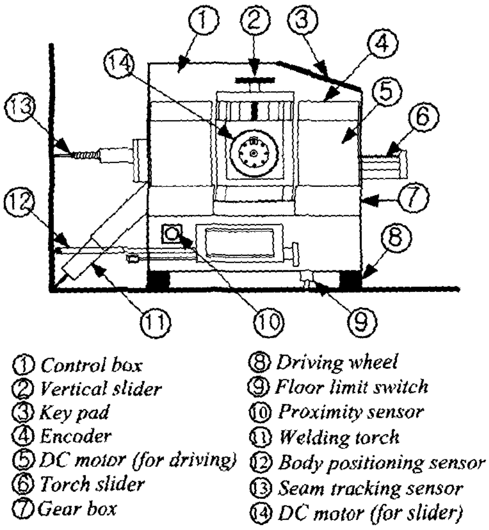


Fig. 1 Configuration of the developed welding mobile robot

Fig. 2 shows the torch slider system with the seam tracking sensor and body positioning sensor. It consists of torch holder, torch slider and a potentiometer type of seam tracking sensor. A potentiometer type of tracking sensor has a spring and a ball bearing at the tip of torch slider system and is built up on the top position of the torch holder. A rack-pinion type of the torch slider is designed to be controlled horizontally by a DC motor to track the curved seam line when the robot is turning at a corner of lattice box.

Body positioning sensor is used for the control of the direction and the posture of mobile robot when the mobile robot moves along straight welding line. It also has potentiometer. a bearing with a diameter of 4mm is installed inside it to track the filet wall smoothly. A spring is also installed inside it and the sensor moves forward and backward when the robot moves to the filet wall and goes far from the filet wall, respectively.

The sensor measures the displacement seam the values of tracking sensor and body positioning sensor is classified into 11 patterns as shown in Table 1 and controls the direction and the posture of mobile robot.

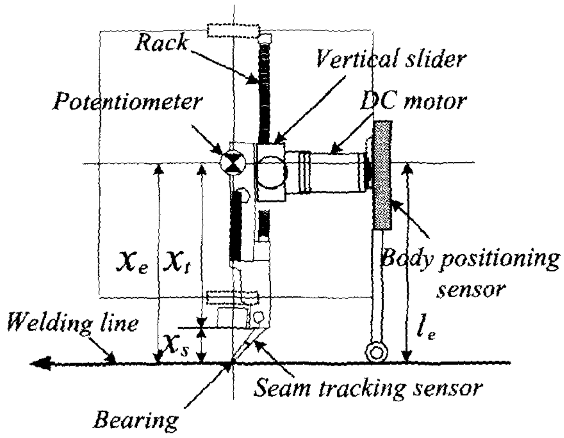


Fig. 2 Configuration of torch slider system with seam tracking sensor

2.2 Control Device

Fig. 3 shows the composition of the controller part in which main control unit is constructed by Intel 16 bits 80c196kc microprocessor.

HSI (High speed Input) port receives inputs the encoder's signals of the driving motor of right, left wheels and torch slider. A/D converter channel receives the signals of seam tracking sensor and body positioning sensor.

The PWM signals for driving three motors such as two wheels and a torch slider are generated by HSO (High speed output) port. The welding conditions are put into the main controller through a keypad with 7-segment display. The motor driving devices are designed and made up to be arbitrarily controlled according to a specified velocity using independent modules.

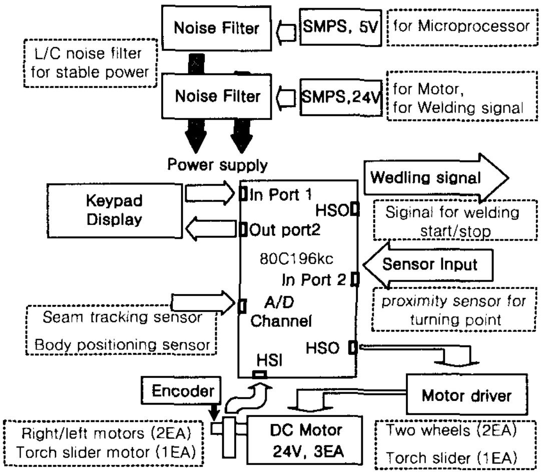


Fig. 3 Composition of the controller

3. Control Algorithm of Mobile Robot

3.1 Welding pattern of the welding mobile robot

Fig. 4 is a diagram of the mobile robot operating patterns of welding process in a lattice box for welding with seam tracking. After setting the welding conditions and the initial values through the keypad and positioning the robot appropriately in a lattice box, the power switch for welding is turned on. In (a), the robot is moving to the fillet wall until the proximity sensor detects a wall. In (b), the mobile robot turns until getting the preset initial values of the seam tracking and body positioning sensors that are regarded as the reference values for the lengths of torch slider(x_e) and the body positioning sensor(l_e).

After getting the preset initial values from the sensors, the mobile robot goes to straight line without any welding. In (c) and (d), the mobile robot detects the welding starting point, turns and starts welding with specified velocity when the proximity sensor positioned at the front side detects a wall while the mobile robot is moving along the straight line. At the same time of turning, the robot is lengthening or shortening the torch slider according to the turning position. After the corner welding, the robot is starting the welding motion of straight line when the sensor values of the seam tracking sensor and the body positioning sensor are the same to the initial values.

In (e), the mobile robot continues welding until getting to welding starting point. The mobile robot stops welding when the welding stopping point in (f) is the same to the welding starting point in (c).

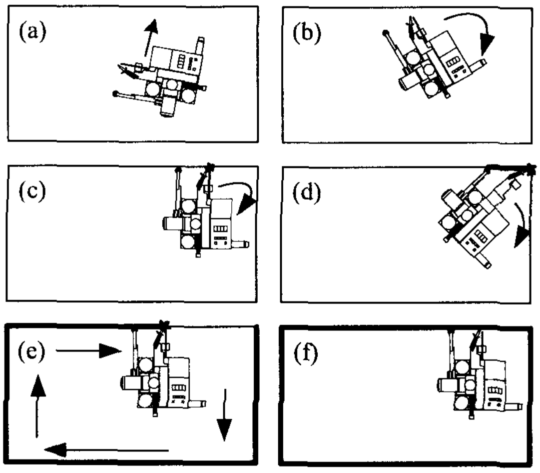


Fig. 4 The diagram of operating patterns for a welding process

3.2 Seam tracking control algorithm

Fig. 5 describes a configuration for the displacement of welding seam tracking sensor when the mobile robot is moving along straight line or curved line.

To control the length of the torch slider corresponding to the displacement of the seam tracking sensor, we introduce a model of the torch slider system shown in Fig. 2. A controller for the torch slider is given by using the information for the displacement of the seam tracking sensor. Using the Newton's second law to the rotor of torch slider, we can get the following equation[1].

$$J_t \frac{d^2\theta_t}{dt^2} + D_t \frac{d\theta_t}{dt} = \tau_t \qquad (1)$$

In order to express Eq. (1) into an equation related with the length of the torch slider, let us multiply radius of pinion (r_p) at the both sides of Eq. (1), and substitute new state $\ddot{x}_t$ for $J_t \frac{d^2\theta_t}{dt^2}$ and $\dot{x}_t$ for $D_t \frac{d\theta_t}{dt}$ because $r_p\theta_t$ is the length of torch slider (x_t) . Thus, we can obtain:

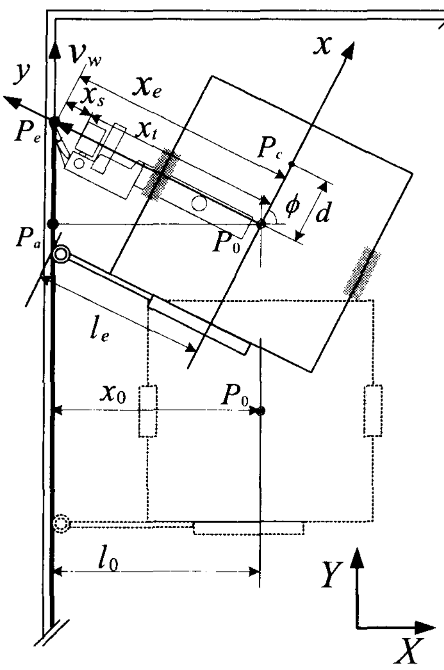


Fig. 5 Configuration for the displacement of seam tracking sensor

$$\ddot{x}_t = -A\dot{x}_t + B\tau_t \tag{2}$$

where,

$$A = \frac{D_t}{J_t},\ B = \frac{r_p}{J_t}$$

In Fig. 5, we can calculate the length of the seam tracking sensor (x_s) as follows :

$$x_s = \begin{cases} \dfrac{x_o}{\sin\phi} - x_t = l(x_o, x_t, \phi) : 0 \le x_s \le l_s \\ l_s \qquad\qquad\qquad : x_s \succ l_s \end{cases} \tag{3}$$

where, $\phi = \frac{r}{2b}(\theta_r - \theta_l)$

We designed the controller by a PID control method To control torch slider for seam tracking sensor. The tracking error for seam tracking sensor and the control input for the torch slider (u_s) as torque acting on torch slider (τ_t) are giving as follows :

$$e_s = x_s^d - x_s \tag{4}$$

$$u_s = K_{PS}\, e_s + K_{IS}\int e_s\, dt + K_{DS}\, \dot{e}_s \tag{5}$$

where, x_s^d is the desired displacement of seam tracking sensor.

3.3 Motion control of straight welding line

Two motors are used for motion control of mobile robot. If there is a velocity error between two motors, the posture of the mobile robot is changed according to the error. For good welding, the welding velocity should be kept constantly. In addition, two motors must be controlled simultaneously to satisfy two conditions such as keeping constant velocity and tracking straight welding line. But the control is very difficult in the case of using the modeling equation of mobile robot. Furthermore, when we realize the control by using one chip microprocessor, the control based on the modeling is very complicated by the limitation of its arithmetic calculation. Thus, a simplified control technique is needed. In this paper, the right side motor of the mobile robot is controlled by adopting PD control method and the other is driven by using posture pattern of the body based on two errors for seam tracking sensor on torch slider and the body positioning sensor. That is, the left motor is purposed for the constant welding velocity control and the right motor is oriented for posture control

Using the Newton's second law to the right motor, we can get the following equation. The right motor input u_p is controlled by using PD control method as follows :

$$J_r \frac{d^2\theta_r}{dt^2} + D_r \frac{d\theta_r}{dt} = \tau_r \tag{6}$$

$$u_p = (K_{PP} e_p + K_{DP} \dot{e}_a) \tag{7}$$

$$v = \begin{bmatrix} v_r \\ v_l \end{bmatrix} = \begin{bmatrix} r & 0 \\ 0 & r \end{bmatrix} \begin{bmatrix} \dot{\theta}_r \\ \dot{\theta}_r \end{bmatrix} \tag{8}$$

$$e_p = v^d - v_r$$

where, v^d , v_r and v_l are the velocities of reference right and left wheels of mobile robot, respectively. We calculated each gain for Eq. (7) by using Ziegler-Nichols method[9].

The posture control is done by using two sensors such as seam tracking sensor on torch slider and body positioning sensor attached on the robot body. According to the errors between two sensors deviated from those initial error values, the posture patterns of the robot are divided into eleven types as shown in Table 1.

The mobile robot must be controlled to satisfy the initial value of the two sensors. The preset initial value has a range with 140±3 ㎜. The mobile robot moves to the fillet wall until the range of the preset initial value is obtained. If the values detected from the sensors satisfy the range, the mobile robot regards the value as the initial value and set up the value as the initial value.

According to the posture of the mobile robot as shown in Table 1, the straight locomotion is controlled such that the velocity of the right wheel is varied under the condition of the constant velocity for the left wheel.

Table 1 Posture patterns of mobile robot

No.	Error values $x_{ee} = x_e - x_0$, $l_{ee} = l_e - l_0$	Body postures	v_r
1	$x_{ee} = 0, l_{ee} = 0$	OK	-
2	$x_{ee} > 0, l_{ee} = 0$	CW direction	up
3	$x_{ee} < 0, l_{ee} = 0$	CCW direction	down
4	$x_{ee} = 0, l_{ee} > 0$	CCW direction	down
5	$x_{ee} = 0, l_{ee} < 0$	CW direction	up
6	$x_{ee} > 0, l_{ee} < 0$	CW direction	up
7	$x_{ee} < 0, l_{ee} > 0$	CCW direction	down
8	$x_{ee} > 0, l_{ee} > 0$ $(x_{ee} > l_{ee})$	go for from the welding line (CW)	up
9	$x_{ee} > 0, l_{ee} > 0$ $(x_{ee} < l_{ee})$	go for from the welding line (CCW)	up
10	$x_{ee} < 0, l_{ee} < 0$ $(l_{se} > l_{ee})$	go for from the welding line (CW)	down
11	$x_{ee} < 0, l_{ee} < 0$ $(x_{ee} < l_{ee})$	go for from the welding line (CCW)	down

l_{ee} : the difference between the initial body posture and current body posture
x_{ee} : the difference between the initial torch slider and current torch slider

3.4 Turning motion control

A proximity sensor detects the rotation point at corner, and then, the robot rotates the corner for welding and its torch slider is controlled for the electrode end point to be kept at the welding target line. When the robot is driven at corner in the lattice box space, the left and right wheels are driven in the opposite direction, respectively. The absolute velocity of two wheels is exactly equal. Also, the mobile robot has square structure and the electromagnet installed in the center of the robot. So, the electromagnet prevents to stray away from turning point. We can assume that the forward velocity of the mobile body is zero and the mass center of mobile robot is the geometrical center point of the robot-the distance form P_0 to mass center of mobile robot d is zero. Thus, the mobile robot turns with right and left wheels rotating in the opposite direction around the center. We can derive the welding velocity v_w angular velocity error e_a and input u_a producing torque of left and right wheels as follows :

$$v_w = \frac{d}{dt}(\overline{P_a P_e}) = \frac{d}{dt}(x_e \cos\phi) = \dot{x}_e \cos\phi - x_e \dot{\phi} \sin\phi$$

$$= \frac{d}{dt}\left(\frac{x_o}{\sin\phi}\right)\cos\phi - x_o\dot{\phi} = v(q) \tag{9}$$

$$e_a = -\frac{\sin\phi^2 v_w}{x_o} - \dot{\phi} \tag{10}$$

$$u_r = (K_{PT}e_a + K_{DT}\dot{e}_a)\begin{bmatrix} -1 \\ 1 \end{bmatrix} \tag{11}$$

4. Experimental Results

To show the effectiveness of the developed mobile robot, the practical welding experiment is done under the welding condition of Table 2 and the lattice with dimension of 1m X 1.5m X 0.2m by compositing of the welding system shown in Fig. 6. Other parameters are given in reference[1].

Photo 2 shows the welding spectacle of the developed mobile robot. The previous state equations (5), (7) and (11) are transformed into discrete type with the sampling time of 10ms and are applied to experiment.

Fig. 7 shows the experimental results for straight locomotion at the welding velocity of 45cm/min. Fig. 7(a) shows the velocities of two wheels. The continuous line and the dotted line show the velocity of left wheel and right wheel, respectively. It is shown that the left wheel is controlled as the constant velocity of 45cm/min and the right wheel is controlled by acceleration and deceleration for welding seam tracking and robot posture control. In Fig. 7(b), the continuous line is x_e the distance between the torch sensor end point and P_o and l_e the distance between the posture sensor end point and P_o. The initial lengths of x_e and l_e are 140mm. The fluctuation of the position value of the posture sensor form 35 second to about 55 second are fluctuations of x_e and l_e. In welding, these are produced by floor indents and obstacles considered as disturbances for body posture. Although these disturbances exist, welding torch slider is always controlled as constant value. The velocity of right wheel is controlled against the disturbance as shown in Fig. 7(a). x_e always keeps 140mm. However, l_e are fluctuated and then converges to x_e by overcome the disturbances after some time intervals. That is, this is for l_e to be x_e 140mm. Fig. 7(c) shows welding velocity. The welding velocity is controlled as the constant velocity of 45cm/min.

In Eq. (5), (7) and (11), each gains are chosen as $K_{PS} = 150$, $K_{IS} = 0.5$, $K_{DS} = 80$, $K_{PP} = 0.8$, $K_{DP} = 0.06$, $K_{PT} = 0.75$ and $K_{DT} = 0.06$.

Fig. 8 shows the experimental results for rotational locomotion with welding velocity of 45 cm/min. In Eq. (10), the proportional and derivative gains are chosen as $K_{PT} = 0.65$, $K_{DT} = 0.18$, Fig. 8(a) shows angular velocity of left and right wheels. The dotted line, the continuous line and the phantom line are the theoretically calculated angular velocity of left and right wheels, the controlled angular velocity of right wheel and the controlled angular velocity of left wheel, respectively. The difference between the theoretically calculated angular velocity and the controlled angular velocity is produced by the slip in rotation. Fig. 8(b) shows the position of torch slider. that is, it shows the distance that torch slider moves forward to the fillet and backward from the fillet wall when the robot rotates for welding the corner of lattice.

Fig. 8(c) shows the welding velocity of the electrode end point. photo 2 shows actual welding with mobile robot. Photo 3 shows the welded bead obtained through the experiment. Although in the experiment there is some fluctuation in the welding velocity, we can see that the welded bead is excellent.

Table 2 Experimental condition of welding system

Work piece	Mild steel (4mm)
Welding wire	Ø1.2 Flux cored wire
Welding Current	200A
Welding Voltage	25V
Shield Gas	18ℓ/min CO2

Photo 2 Actual welding with mobile robot

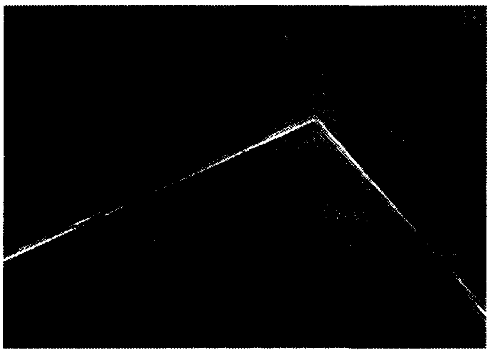


Photo 3 Bead-seam tracking performance of mobile robot

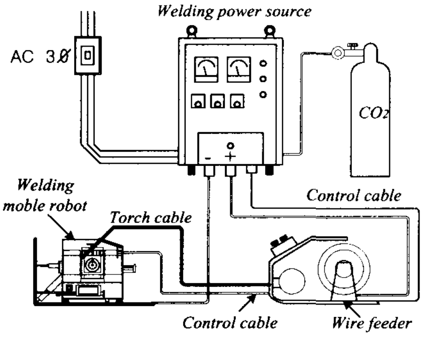
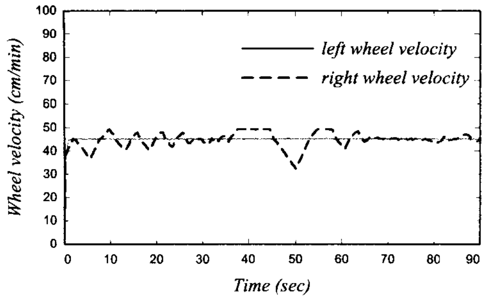
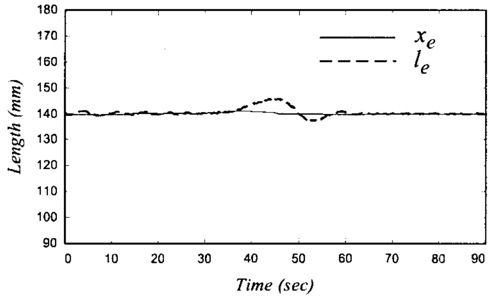


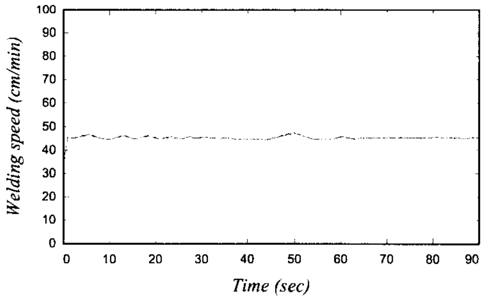
Fig. 6 Schematic diagram of welding system



(a) velocity of left and right wheels

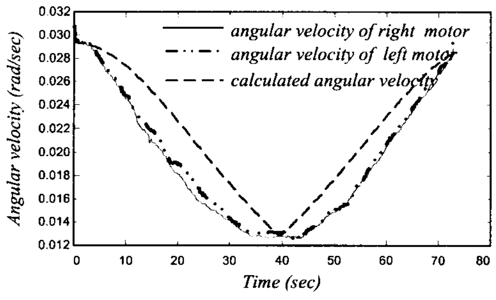


(b) position of torch and posture sensors

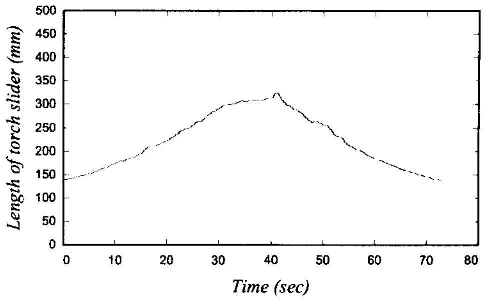


(c) welding velocity

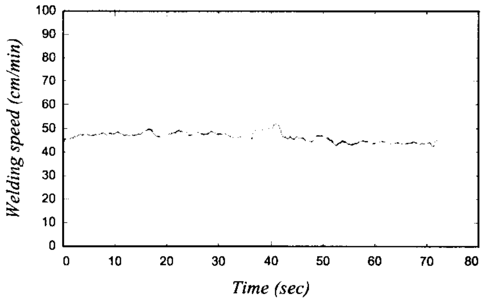
Fig. 7 Experimental results for straight locomotion (welding velocity : 45cm/min)



(a) angular velocity of left and right wheels



(b) position of torch slider



(c) welding velocity

Fig. 8 Experimental results for turning locomotion (welding velocity : 45cm/min)

5. Conclusions

This paper proposed PID controller for torch slider and PD controller for motor right wheel. to control the motion of two-wheeled welding mobile robot with seam tracking sensor touched on welding line. A welding mobile robot to implement straight and corner welding in lattice based on the above method are developed and the experimental results are shown. The motion control is divided into 3 types of straight, turning and seam tracking controls. The motion control is realized in the view of keeping constant welding velocity and precise seam tracking even though the target welding line is on straight or curved one. To show the effectiveness of the developed mobile robot, the practical welding experiment is done for a lattice box. Through the experimental results, we can see that the position value of the electrode end point and the welding velocity are controlled almost constantly in spite of straight and turning locomotion. As the result, it is expected that the developed mobile robot can be applicable to automatic welding in several industrial fields.

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