Decoupling and Robust Adaptive Control of Omnidirectional, Automated Guided Vehicle Based on Nonguided Line Navigation System*

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This paper is concerned with a control system design for the new type of omnidirectional AGV (automated guided vehicle) without any steering mechanisms. The system is regarded as a highly nonlinear multidimensional system with parameter uncertainties, so the conventional control techniques are not available. Here we propose a new control algorithm by combining nonlinear decoupling control with robust simple adaptive control (SAC). Both techniques were developed by one of the authors. The control system then results in single-input and single-output (SISO) control systems by the effect of decoupling control, and the control accuracy is assured by robust SAC. The effectiveness of the proposed method is confirmed through numerical simulations.

Key Words: Automatic Control, Adaptive Control, Moving Robot, Automated Guided Vehicle, Decoupling Control, Robust Adaptive Control, Omnidirectional Vehicle

1. Introduction

Automated guided vehicles (AGVs) and robot manipulators play a very important role in the field of factory automation. To date, AGVs based on electromagnetic and optically guided line systems have been the most common in the majority. Considering the severe social circumstances surrounding the production environment, however, we need to develop AGVs based on nonguided line systems. Hence much research relating to AGVs has been conducted lately[1].

This paper is concerned with a control design method for such an AGV. Having a simple mechanism and diversity of moving mode, omnidirectional AGVs without any steering mechanisms are remarkable from the practical point of view. In regard to this kind of AGV, very few examples, such as the trochoid propulsion type[2] and 3-wheel type[3], have been developed. The new type of omnidirectional AGV presented here is based on a 4-wheel driving system and each drive wheel is built up by a number of free-rolling rollers placed at an angle of 45° on a rim. With the appropriate choice of the combination of rotating direction of 4-drive wheels, an omnidirectional moving mode can be arbitrarily obtained. With respect to the degree of freedom for designing the vehicle in terms of shape and stability of wheel in traveling, this AGV is superior to the above-stated two examples.

However, this vehicle system is regarded as a highly nonlinear multi-input and multi-output (MIMO) system involving interactions between inputs and outputs, so that the conventional control techniques are not available. Therefore, we proposed a new motion control algorithm by combining nonlinear decoupling control with robust SAC. Assuming that the dynamics of omnidirectional AGV is governed by the exact mathematical model and all parameters are known, the obtained ideal nonlinear MIMO vehicle system results in three linear SISO decoupled systems by use of nonlinear controllers[4]. Therefore the conventional linear control theories can be applied to these systems. Unfortunately there exist some

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uncertainties such as parameter identification errors, the imbalance generated from the amount and the position of load on the vehicle. Therefore, perfect decoupling of the actual system is not guaranteed. To avoid such a difficulty, robust SAC[(5),(6)] on the basis of the assumption that these uncertainties are regarded as disturbances is applied here to actual systems so that the position and attitude control accuracy can be assured.

The new control system design method proposed here is performed in two steps. In the first step, a quasi-decoupling control system is obtained by state variable feedback control based on nominal values of plant parameters and approximate nonlinear functional structures. In the next step, the robust SAC is applied to the quasi-decoupling system obtained in the first step to improve the control accuracy. It is noted that the robust SAC has a very simple adaptive control structure compared with the conventional adaptive control algorithms, and it also has good robust control characteristics in spite of the existence of disturbances.

Though the final goal of our research is to confirm the effectiveness of this control design method by applying it to an actual vehicle system, we present here numerical simulation in advance to confirm the control performance.

2. Mathematical Model of the New Type of Omnidirectional AGV

The wheel system to be controlled here is based on a 4-wheel drive system and each drive wheel is built by a number of free-rolling rollers placed at an angle of 45° on a rim, as shown in Fig. 1 [(7)]. With the appropriate choice of the combination of rotating direction of 4 drive wheels, an omnidirectional moving mode including forward, backward, right, left, diagonal and turning modes and the combination of these modes can be arbitrarily obtained. Providing a positive rotation to each of the four driving wheels, the driving forces shown in Fig. 2 are generated. In the coordinate system as shown in Fig. 2, the following equation of motion with respect to the x-axis, y-axis and rotation around the center of gravity of vehicle can be obtained, provided that some uncertainties such as frictions existing in the vehicle system are negligible.

$$M\ddot{x}_G(t) = -f_{fr}(t)\sin\{45^\circ-\theta(t)\} - f_{rl}(t)\sin\{45^\circ-\theta(t)\} + f_{fl}(t)\sin\{45^\circ+\theta(t)\} + f_{rr}\sin\{45^\circ+\theta(t)\} \quad (1\cdot a)$$

$$M\ddot{y}_G(t) = f_{fr}(t)\cos\{45^\circ-\theta(t)\} + f_{rl}(t)\cos\{45^\circ-\theta(t)\} + f_{fl}(t)\cos\{45^\circ+\theta(t)\} + f_{rr}\cos\{45^\circ+\theta(t)\} \quad (1\cdot b)$$

$$I\ddot{\theta}(t) = -f_{fr}(t)\sin\{45^\circ+\phi\}\cdot l + f_{fl}(t)\cos\{45^\circ-\phi\}\cdot l - f_{rr}(t)\cos\{45^\circ-\phi\}\cdot l + f_{rl}\sin\{45^\circ+\phi\}\cdot l \quad (1\cdot c)$$

In Eq.(1), M and I denote the mass and the moment of inertia of vehicle, respectively, and f_{fr}, f_{fl}, f_{rr} and f_{rl} are the driving forces actuating each wheel.

Let us define the state variables, input variables and output variables as follows.

$$x(t) = [x_1(t), x_2(t), x_3(t), x_4(t), x_5(t), x_6(t)]^T = [x_G(t), \dot{x}_G(t), y_G(t), \dot{y}_G(t), \theta(t), \dot{\theta}(t)]^T$$

$$u(t) = [u_1(t), u_2(t), u_3(t), u_4(t)]^T = [f_{fr}(t), f_{fl}(t), f_{rr}(t), f_{rl}(t)]^T$$

$$y(t) = [y_1(t), y_2(t), y_3(t)]^T = [x_G(t), y_G(t), \theta(t)]^T$$

Then, from Eq.(1) the following state equation and output equation are obtained.

$$\dot{x}(t) = a(x) + B(x)u(t) \quad (2\cdot a)$$

$$y(t) = K(x), \quad (2\cdot b)$$

where

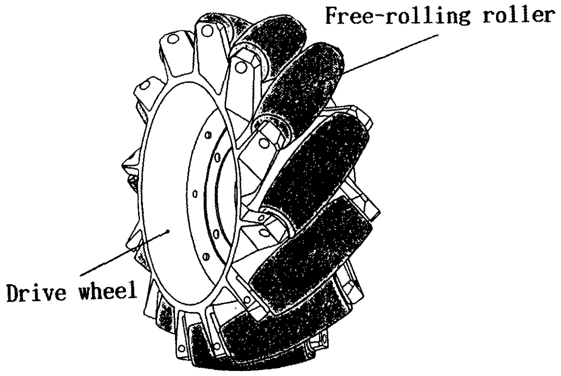

Fig. 1 Wheel

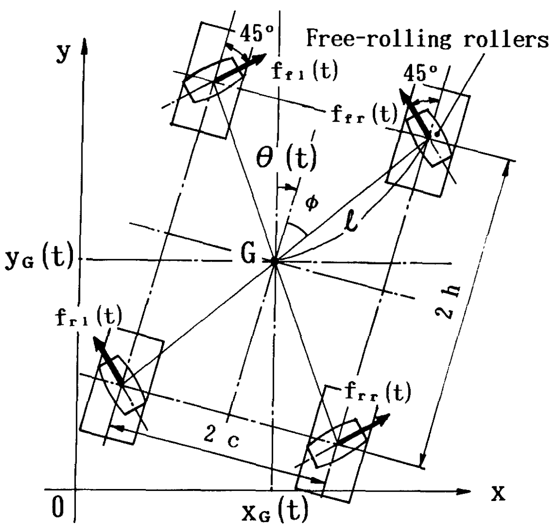

Fig. 2 Vehicle system model

$$a(x)=\begin{bmatrix} x_2(t) \\ 0 \\ x_4(t) \\ 0 \\ x_6(t) \\ 0 \end{bmatrix},$$

$$B(x)=\begin{bmatrix} 0 & 0 & 0 & 0 \\ -a_1(t) & a_2(t) & a_2(t) & -a_1(t) \\ 0 & 0 & 0 & 0 \\ a_2(t) & a_1(t) & a_1(t) & a_2(t) \\ 0 & 0 & 0 & 0 \\ -b & b & -b & b \end{bmatrix},$$

$$K(x)=\begin{bmatrix} x_1(t) \\ x_3(t) \\ x_5(t) \end{bmatrix}$$

and

$$a_1(t)=\{\cos x_5(t)-\sin x_5(t)\}/(\sqrt{2}M)$$
$$a_2(t)=\{\cos x_5(t)+\sin x_5(t)\}/(\sqrt{2}M)$$
$$b=\phi_1\cdot l/I,\ \phi_1=(\cos\phi+\sin\phi)/\sqrt{2}.$$

The vehicle system expressed by Eq.(2) is a nonlinear MIMO system including linear input variables. There also exists some interaction between inputs and outputs. The dimension of the input vector is fourth order. However, in order to realize a nonlinear decoupling control system, as described later, in this vehicle system, we need at most three input variables. There are six combinations for choosing three inputs from four inputs. Here the following three inputs are chosen as input variables on the basis of several simulation runs in an open-loop system. In the simulations, the combination of the above-mentioned three inputs gave the minimum driving energy consumption.

$$u(t)=[u_1(t),\ u_2(t),\ u_3(t)]^T$$
$$=[f_{fl}(t)=f_{rr}(t),\ f_{fr}(t),\ f_{rl}(t)]^T \tag{3}$$

By choosing the above inputs, $B(x)$ can be rewritten as

$$B(x)=\begin{bmatrix} 0 & 0 & 0 \\ 2a_2(t) & -a_1(t) & -a_1(t) \\ 0 & 0 & 0 \\ 2a_1(t) & a_2(t) & a_2(t) \\ 0 & 0 & 0 \\ 0 & -b & b \end{bmatrix} \tag{4}$$

3. Decoupling Control for Nonlinear MIMO Systems Containing Input Variables Linearly[4]

Let us consider a new input vector of order r which corresponds to the r-th output vector. In order to realize a one-to-one correspondence between setpoints $v(t)$ and output variables $y(t)$, we use the following state variable feedback control law:

$$u(t)=f^*(x)+G^*(x)v(t), \tag{5}$$

where $v(t)$ is the r-th order new input vector. According to the nonlinear decoupling theory developed by Tokumaru and Iwai [4], decoupling can be attained by choosing vector $f^*(x)$ of order r and $r\times r$ matrix $G^*(x)$ in Eq. (5) as follows.

$$f^*(x)=-H(x)^{-1}\{n^*(x)+n_1(x)\} \tag{6•a}$$
$$G^*(x)=H(x)^{-1}, \tag{6•b}$$

where

$$H(x)=\begin{bmatrix} \left(\dfrac{\partial J_{1,\ \rho_1}(x)}{\partial x}\right)B(x) \\ \cdots \\ \left(\dfrac{\partial J_{r,\ \rho_r}(x)}{\partial x}\right)B(x) \end{bmatrix} \tag{7}$$

$$n^*(x)=\begin{bmatrix} J_{1},\ \rho_1+1(x) \\ \cdots \\ J_{r},\ \rho_r+1(x) \end{bmatrix},\ n_1(x)\begin{bmatrix} \sum_{j=0}^{\rho_1}\lambda_{1j}J_{1j}(x) \\ \cdots \\ \sum_{j=0}^{\rho_r}\lambda_{rj}J_{rj}(x) \end{bmatrix},$$

where $\rho_i\geq 0\,(i=1, 2, \ldots, r)$ are defined as relative degrees of the nonlinear system by the following relations.

$$\left(\frac{\partial J_{i,o}(x)}{\partial x}\right)B(x)=\cdots=\left(\frac{\partial J_{i,\ \rho_i}-1(x)}{\partial x}\right)B(x)\equiv 0$$
$$\left(\frac{\partial J_{i,\ \rho_i}(x)}{\partial x}\right)B(x)\neq 0, \tag{8}$$

where

$$J_{i0}(x)=K_i(x)$$
$$J_{ik}(x)=\left(\frac{\partial J_{i,\ \rho_k}-1(x)}{\partial x},\ a(x)\right),\ k=1, 2, \cdots, n-1. \tag{9}$$

Here (,) denotes the inner product of the two operands, λ_{ij} are arbitrary constants, and $K_i(x)$ is the i-th element of vector $K(x)$ in Eq.(2•b).

4. Decoupling and Robust Adaptive Control

4.1 Decoupling control

The motion control system of AGV proposed here includes two kinds of control algorithms. Roughly speaking, the AGV system, which is considered as a highly nonlinear system, is first decoupled approximately by a nonlinear decoupling control algorithm based on the knowledge of system nominal parameters. Then, we apply an adaptive control algorithm to each decoupled SISO system to attain the control accuracy. Let the dynamics of omnidirectional AGV be expressed by the mathematical model Eq.(2). Then the state variable feedback law Eq.(5) is given by

$$H(x)^{-1}=\begin{bmatrix} \dfrac{a_2(t)}{2\Delta} & \dfrac{a_1(t)}{2\Delta} & 0 \\ -\dfrac{a_1(t)}{2\Delta} & \dfrac{a_2(t)}{2\Delta} & -\dfrac{1}{2b} \\ -\dfrac{a_1(t)}{2\Delta} & \dfrac{a_2(t)}{2\Delta} & \dfrac{1}{2b} \end{bmatrix} \tag{10}$$

$$n^*(x)=\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix},\ n_1(x)=\begin{bmatrix} \lambda_{10}x_1(t)+\lambda_{11}x_2(t) \\ \lambda_{20}x_3(t)+\lambda_{21}x_4(t) \\ \lambda_{30}x_5(t)+\lambda_{31}x_6(t) \end{bmatrix},$$

Here, relative degrees of the system are $\rho_1=\rho_2=\rho_3=1$, and $\Delta=a_1(t)^2+a_2(t)^2$. In regard to the observation of state variables, a navigation system is adopted here on the assumption that two accelerometers in the x-axis and y-axis, and one gas rate gyroscope are installed in the vehicle. All the state variables then can be detected directly or indirectly.

Suppose that the system (nominal) parameters are known. Then, applying the above-stated decoupling state variable feedback control law to a nonlinear plant with three inputs and three outputs yields three SISO linear decoupled systems represented by

$$\ddot{y}_i(t)+\lambda_{i1}\dot{y}_i(t)+\lambda_{i0}y_i(t)=v_i(t),\ i=1,2,3. \quad (11)$$

Therefore, the position of the center of gravity $x_G(t)$, $y_G(t)$ and attitude $\theta(t)$ of the vehicle can be specified independently by each new input $v_i(t)$. Therefore, the control problem results in the conventional design problem for three linear SISO systems given by Eq.(11). In the actual implementation, however, there exist several uncertainties such as parameter identification errors of vehicle systems, the imbalance generated from the amount and the position of load on vehicle, friction between wheel and the floor and undulation of the floor and so on. In such cases, the decoupling control law constructed under the ideal situation no longer guarantees perfect decoupling.

In order to cope with this problem, we introduce the following SAC technique as the second step design procedure.

4.2 Robust simple adaptive control[5],[6]

Under the assumption that plant parameters and nonlinear elements are known, we constructed the decoupling control system in the preceding paragraph. Only their nominal values, however, are known in ordinary circumstances. In that case, the actual control system based on these nominal values can be obtained not in Eq.(11), but in the following form:

$$\ddot{y}_i(t)+\lambda_{i1}\dot{y}_i(t)+\lambda_{i0}y_i(t)=v_i(t)+f_i(t,y,\dot{y}),\quad i=1,2,3, \quad (12)$$

where $f_i(\ \ )$, the second term on the right-hand side of Eq.(12), called here the "disturbance term", denotes the term lumping together parameter variations, unknown nonlinear characteristics and disturbances.

We can obtain the following representation in the form of a state equation from Eq.(12).

$$\begin{aligned}\dot{x}_{pi}(t)&=A_{pi}x_{pi}(t)+b_{pi}v_i(t)+b_{pi}f_i(t)\\ y_i(t)&=c_{pi}{}^Tx_{pi}(t),\ x_{pi}\in R^{2\times1}\end{aligned} \quad (13)$$

The stable SISO reference model to be followed can be represented by

$$\begin{aligned}\dot{x}_{mi}(t)&=A_{mi}x_{mi}(t)+b_{mi}u_{mi}(t)\\ y_{mi}(t)&=c_{mi}{}^Tx_{mi}(t),\ x_{mi}\in R^{2\times1}.\end{aligned} \quad (14)$$

Here, $u_{mi}(t)$ denotes the i-th reference command input and $y_{mi}(t)$ is the i-th reference model output to be followed by the i-th plant output $y_{pi}(t)$.

The problem is to find a control law $v_i(t)$ such that

$$\lim_{t\to\infty}e_{yi}(t)=\lim_{t\to\infty}\{y_i(t)-y_{mi}(t)\}=0$$

for the system described by Eq.(13) having unknown parameters and unknown disturbances. For such a problem, adaptive control techniques are said to be useful. However, usual adaptive control methods are not only too complex in structure, but also non robust to disturbances[8]. Recently, the so-called simple adaptive control (SAC) method has received attention as a means of improving the difficulties existing in the adaptive control techniques [5],[6],[9]. The special features of the SAC method are its simple adaptive controller structure, and robustness concerning disturbances and parasitics. Hence, we use this SAC algorithm as the adaptive control algorithm to establish the control accuracy of the AGV control system. The SAC method is applied to the decoupled system Eq.(13). In the following, we will show the specific design procedure.

Assume that there exists unknown constant $\rho_0>0$ such that

$$|f_i(t)|\le\rho_0. \quad (15)$$

In this case, the new input $v_i(t)$ introduced in the decoupling control law Eq.(5) can be regarded as the new control input in the decoupled system Eq.(13). Then, we can construct an adaptive control input $v_i(t)$ as follows:

$$\begin{aligned}&v_i(t)=\Theta_i(t)^Tz_i(t)+v_{Ri}(t) \quad (16)\\ &\Theta_i(t)=[k_{ei}(t),k_{xi}(t)^T,k_{ui}(t)]^T,\\ &z_i(t)=[e_{yi}(t),x_{mi}(t)^T,u_{mi}(t)]^T,\\ &\Theta_i(t)=\Theta_{Ii}(t)+\Theta_{Pi}(t),\\ &\dot{\Theta}_{Ii}(t)=-\Gamma_{Ii}z_i(t)e_{yi}(t)-\sigma_i(t)\Theta_{Ii}(t),\\ &\Theta_{Pi}(t)=-\Gamma_{Pi}z_i(t)e_{yi}(t),\\ &\Gamma_{Ii}=\Gamma_{Ii}{}^T>0,\ \Gamma_{Pi}=\Gamma_{Pi}^T>0\\ &\sigma_i(t)=\sigma_ie_{yi}(t)^2/(1+e_{yi}(t)^2),\ \sigma_i>0.\end{aligned}$$

$v_{Ri}(t)$, the second term on the right-hand side of Eq.(16), is called the robust adaptive control term and is given by Refs.(6) and (7).

$$v_{Ri}(t)=\begin{cases}-\beta_i(t)^Tz_{\beta i}(t)\mathrm{sgn}\ e_{yi}(t), & |\beta_i(t)^Tz_{\beta i}(t)|>\varepsilon\\ -\{\beta_i(t)^Tz_{\beta i}(t)\}^2e_{yi}(t)/\varepsilon, & |\beta_i(t)^Tz_{\beta i}(t)|\le\varepsilon\end{cases} \quad (17)$$

$$\begin{aligned}&\beta_i(t)=\beta_{Ii}(t)+\beta_{Pi}(t),\\ &\dot{\beta}_{Ii}(t)=\Gamma_{\beta Ii}z_{\beta i}(t)|e_{yi}(t)|-\sigma_{\beta i}(t)\beta_{Ii}(t),\\ &\beta_{Pi}(t)=\Gamma_{\beta Pi}z_{\beta i}(t)|e_{yi}(t)|,\\ &\sigma_{\beta i}(t)=\sigma_{\beta i}e_{yi}(t)^2/\{1+e_{yi}(t)^2\},\ \sigma_{\beta i}>0,\\ &\beta_i(t)=[\beta_{0i}(t),\beta_{1i}(t)]^T,\ z_{\beta i}(t)=[1,|\bar{y}_{pi}(t)|]^T,\end{aligned}$$

where $\Gamma_{\beta Ii}$ and $\Gamma_{\beta Pi}$ are positive-definite symmetric matrices, and ε is a small positive constant which relaxes the chattering phenomenon in the switching process. Here, $\bar{y}_{pi}(t)$ is assumed to be constructed by measurable states. By setting $v_{Ri}(t)=0$ in Eq.(16), the adaptive control law becomes identical to the standard SAC algorithm developed by Bar-Kana and Kaufman [9]. The SAC law with $v_{Ri}(t)$ is called robust SAC in the sense that it has robustness to disturbance in comparison to standard SAC. Here it is stressed that SAC and robust SAC can only be applicable to the so-called ASPR (almost strictly positive real) system. The system is called ASPR if there exists a static output feedback such that the resulting closed-loop transfer function is strictly positive real (SPR). In our case, the linear part of Eq. (12) is $G_{Pi}(s)=1/(s^2+\lambda_{i1}s+\lambda_{i0})$. Hence, it is not ASPR. To solve this problem, we will introduce a parallel feedforward compensator $F_i(s)$. According to Iwai and Mizumoto [5], the augmented plant $G_{ai}(s)\cong G_{Pi}(s)$ becomes ASPR by choosing $F_i(s)=d_i/(s+g_i)$. Furthermore, if we set d_i as a small positive constant, then $G_{ai}(s)\cong G_{Pi}(s)$ holds over a wide range of frequency. It follows that the SAC method can be applied to the thus-obtained augmented system $G_{ai}(s)$. Note that the feedforward compensator $F_i(s)$ can be realized in the control algorithm by way of not hardware but software. The overall structure of the control system for omnidirectional AGV described above is shown in Fig. 3.

5. Numerical Simulations

In order to demonstrate the unique feature in the case of a conventional vehicle with steering mechanisms, two numerical simulation examples are shown here.

Although this new type of AGV system can arbitrarily realize any directional moving mode, simulations were executed for 2 cases. In case 1, the traverse mode : ① moving to the right-hand side by a distance of one meter and ② returning to the starting point after 12 seconds, is examined.

The physical quantities of the experimental vehicle are as follows :

$M=100$ kg, $I=80$ kgm^2, $c=0.4$ m, $h=0.8$ m.

Throughout the entire simulation, the decoupling control algorithm is constructed by using the above-stated system nominal parameter values. Figure 4 shows the results using the usual SAC algorithm. In this case, we made the following assumptions. That is, the vehicle is loaded by a workpiece (steel plate) having a length of 0.506 m, width of 0.506 m, thickness of 0.05 m and weight of 100 kg on the center of gravity of the vehicle. In spite of the vehicle's parameter variation due to the loading workpiece, good tracking performance is obtained by the effect of SAC. In this simulation, we used the following design parameters.

$\lambda_{i1}=1.4$, $\lambda_{i0}=1.0$, $\Gamma_{Ii}=\Gamma_{Pi}=1\,000\cdot I$,

$$A_{mi}=\begin{bmatrix}0 & 1\\ -1.0 & -1.8\end{bmatrix},\ b_{mi}=\begin{bmatrix}0\\1\end{bmatrix},\ c_{mi}^T=[1\ 0]$$

$\sigma_i(t)=\sigma_i=0.01$, $F_i(s)=0.001 \quad (i=1, 2, 3)$

The next simulation is the case when the above workpiece is shifted to a distance of 0.2 m behind the center of gravity of the vehicle. As shown in Fig. 5, output $y_1(t)$ and output $y_2(t)$ perfectly follow each reference model. On the other hand, output $y_3(t)(=\theta(t))$ does not follow the model. This phenomenon may be caused by the offset of the loading workpiece on the vehicle.

Figure 6 shows the improvement of this problem using the robust SAC algorithm. Here, robust adaptation parameters are given as follows :

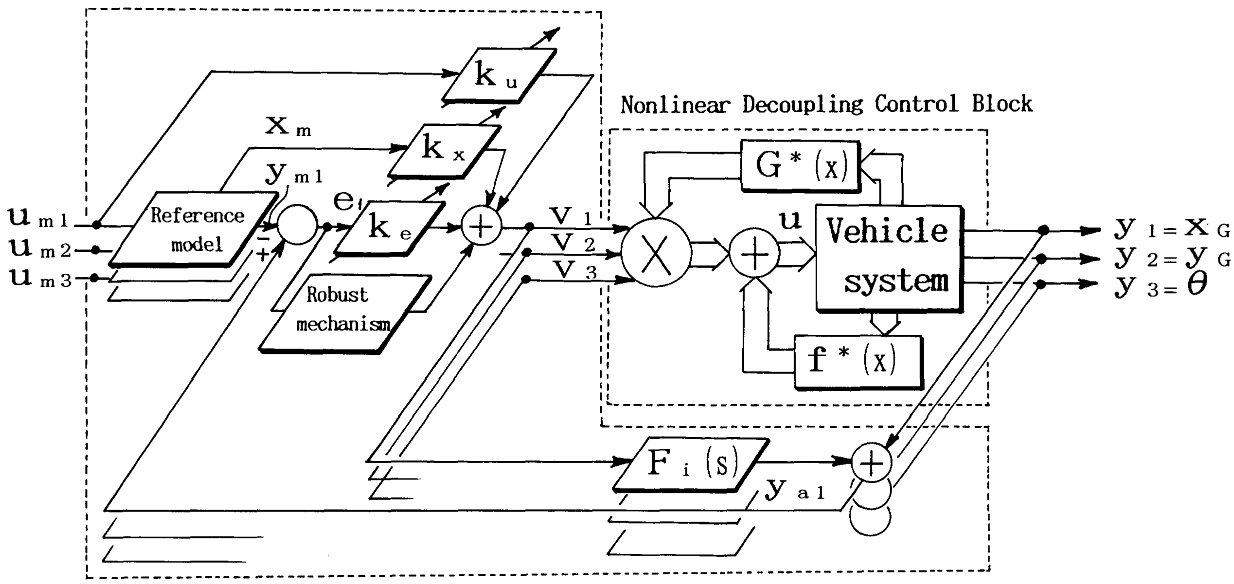

Fig. 3 Control system of omnidirectional AGV

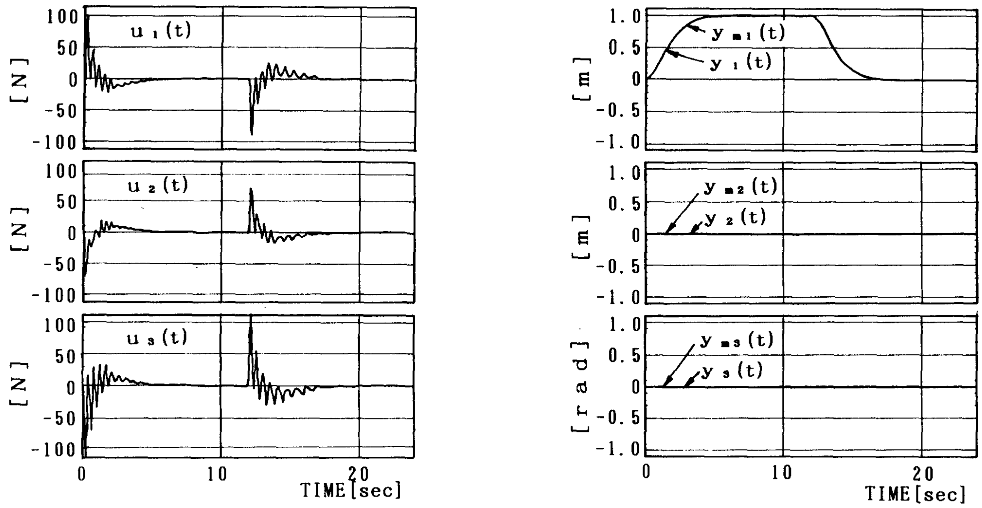

Fig. 4 Responses of outputs and control inputs in decoupled SAC system when the workpiece is loaded on the center of AGV

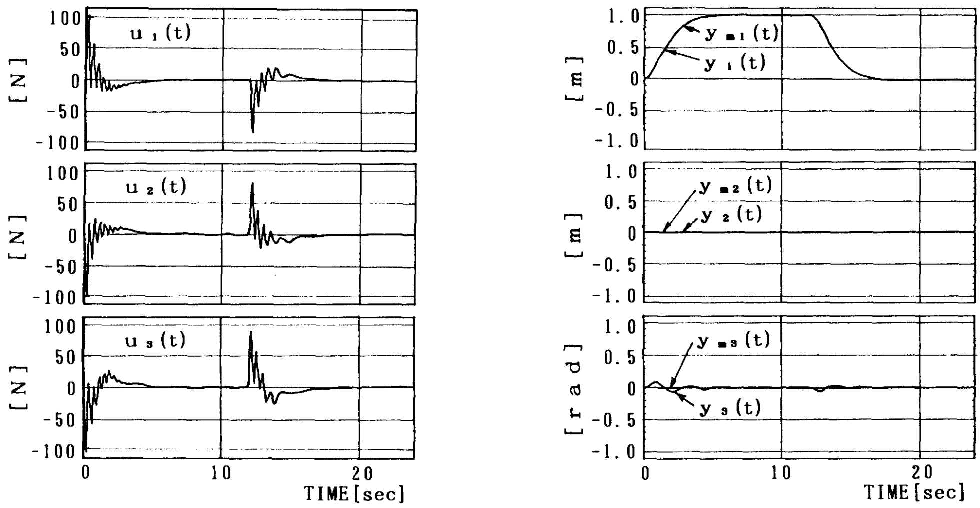

Fig. 5 Responses of outputs and control inputs in decoupled SAC system when the workpiece is loaded at a distance of 0.2 m from the center of AGV

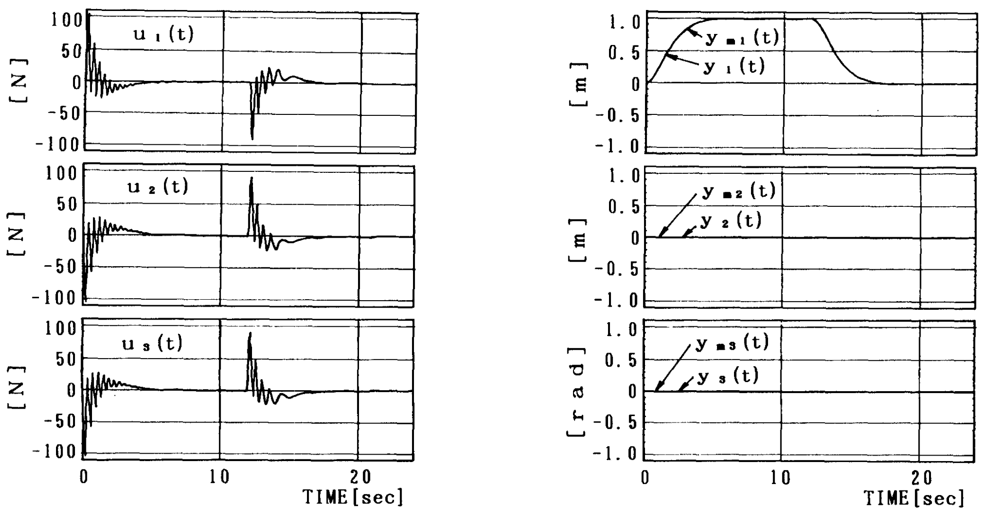

Fig. 6 Responses of outputs and control inputs in decoupled robust SAC system when the workpiece is loaded at a distance of 0.2 m from the center of AGV

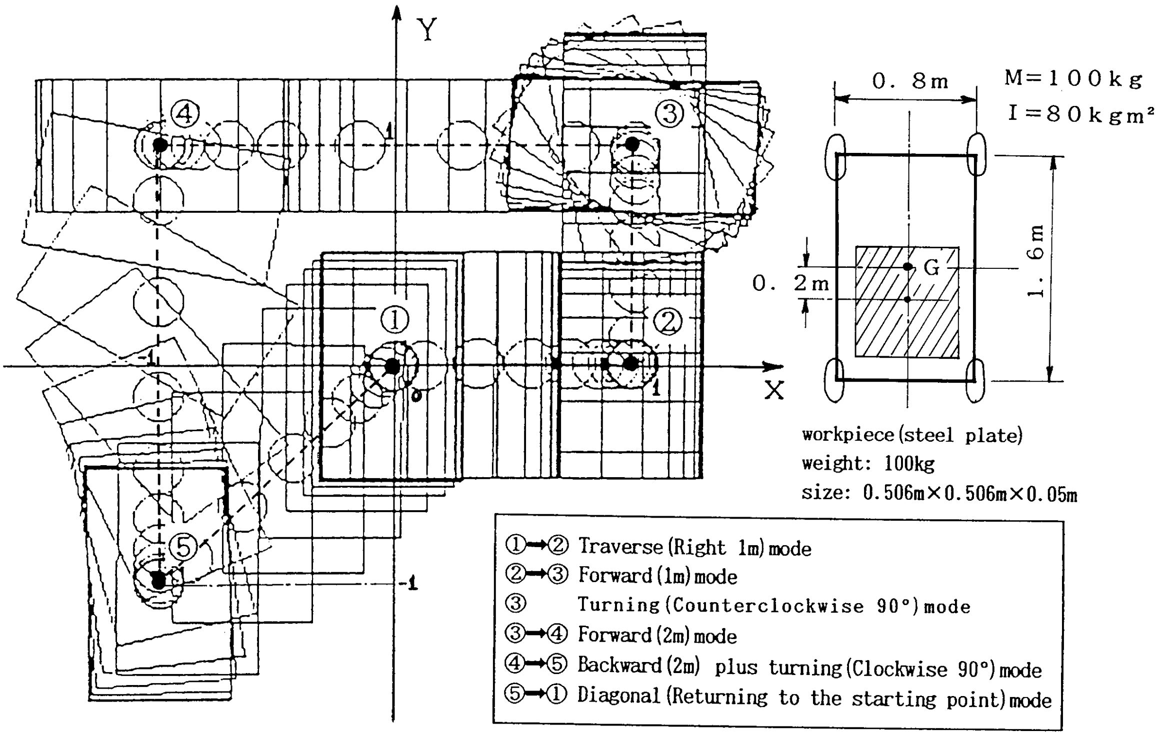

Fig. 7 Motion trajectory of the vehicle

$\Gamma_{\beta_{Ii}}=\Gamma_{\beta_{Pi}}=100\cdot I$, $\sigma_{\beta_i}(t)=\sigma_{\beta_i}=0.01$, $\varepsilon=0.01$.

In case 2, a sequential moving mode is examined under the same set-up given in the simulations shown in Fig. 6. Several modes are indicated, such as ① traverse mode (right), ② forward mode, ③ turning mode (counterclockwise 90 degrees), ④ forward mode, ⑤ turning mode (clockwise 90 degrees) plus backward mode and ⑥ diagonal mode. Figure 7 shows the motion trajectory of the vehicle and we can see the effectiveness of the proposed new control algorithm : nonlinear decoupling control with robust SAC.

6. Conclusions

We have proposed a control system design method for the new type of omnidirectional AGV without any steering mechanisms.

The new control algorithm combining nonlinear decoupling control with robust SAC has the following properties.

(1) The control system does not require any guiding devices.

(2) It realizes position and attitude control arbitrarily. For example, forward, backward, right, left, diagonal, and turning modes and the combinations of these modes can be designated in a simple form.

(3) It does not depend on uncertainties such as the imbalance generated from the amount and the position of load on the vehicle, the friction between wheel and floor, and undulation of the floor.

(4) Desired trajectory of the vehicle can be specified by the so-called reference models.

The effectiveness of the proposed new control design method is confirmed through several numerical simulations.

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