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Competition of Two-wheel Inverted Pendulum Type Robot Vehicle on MCR Course

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Abstract - This paper proposes a competition of inverted pendulum type two-wheeled robot vehicle on MCR (Micom car rally) course. The control theory of inverted pendulum type vehicle is already established. But the control technology used in this system is not commonly in education among undergraduate students of university. The proposed competition will be done by using commercially developed small and low cost robotic vehicles, and is expecting to bring highly educated engineers.

I. INTRODUCTION

Many robot competitions are held in Japan every year. Participants are studying many fields of engineering to develop robots. Each competition has a different rule book, and the knowledge and technology require different levels[1]. MCR(Micom Car Rally)[2] competition was held 14 times, and has been supported by Renesas Technology Corporation from 1996. MCR is one of the contests of line trace robot. Advanced mechatronics technology is required to develop a robot vehicle which runs on a 0.3m width course with straight lines, right-angled corners, s-shaped curves, and lane change points at the high speed. In order to participate in MCR there are many educational elements during development of a micom car which require the knowledge of mechanical engineering, electrical engineering and software engineering. In Japan, many technical high schools are taking in micom cars as a teaching subject. The winner of MCR is clearly understood, because the judgment of this competition is by running time. The time difference appears as a difference of developing technology.

In 2008, 4000 high school students participated in MCR from all over Japan. High school student participants are increasing every year, but there are some problems for a general class of MCR. The general class is able to join with the exception of high school students. Recently, the moving speed of micom car is increasing by using SSM[3-6] control method and specialized tire for MCR course, and the average speed is over 3.5m/s. When undergraduate students of technical universities are first looking at the running speed of micom car at MCR competition, they don't have an interest to join this competition, because they know that much time is needed to build a micom car and to make the control program. From the educational point of view, it is necessary to control the speed by the regulation of this competition. This paper proposes a new competition of robotic car running on the same course as the MCR competition.

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The control of inverted pendulum was started from 1970[7]. In 1988 Yamafuji[8] enabled inverted control of a inverted pendulum vehicle which was constructed with an inverted pendulum, controlled wheels and a posture sensor with touch arm. Recently, inverted pendulum type vehicles are selling under the name as SEGWAY[9]. MEMS(Micro Electro Mechanical Systems) sensor technology enabled miniature and precise gyro scopes which contribute to sense the precise posture angle of the body. Hokuto Dennshi Corp. develops small and low cost inverted pendulum type robot vehicles which are built with MEMS gyro sensor. The competition of inverted pendulum type robot vehicle is able to hold such a situation, and the authors proposes competition by speed with only this type robot at MCR competitions.

This paper shows the control method of line-following for a commercially selling inverted pendulum type vehicle, PUPPY II (Hokuto Dennshi Corp.)[10]. It is assuming that this robot car is running on a MCR course which width is 0.3m, and the trace line is a white line on gray line pasted in the middle of the black acrylic surface. The course is constructed with straight line, s-shape curve, right angle corner, lane change point, and up and down slope. The course setup of MCR is hard and challenging for the inverted pendulum type robot vehicle. At the first step, dynamical equations of PUPPY II are derived by using AUTOLEV[11]. Next, the state feedback gain in discrete time domains for a stable control is derived. Thirdly, the line following method using two reflection type photo interrupters is shown by sensing a gray line. Finally, experimental results show that PUPPY II is able to run smoothly on MCR course, and thus demonstrates the effectiveness control method for inverted pendulum type vehicle. As a results the competition for inverted pendulum type robot vehicle is effective for the education of dynamical system control by using microprocessor. For these reasons, there is a request for a holding organization of MCR competition.

II. MICOM CAR RALLY

A. Technical History

Before the 3rd competition the PWS(Power Wheeled Steering) type vehicles have finished the race, but the steering type ones got the stable lateral control method and dominated the competition until this year. For the PWS type machine[2], the orbit is controlled by the speed difference of each wheel. The position of mass center of this vehicle has to separate from the driving wheels to prevent the pitching vibration by acceleration and deceleration. The improvement of moving speed of PWS type vehicle is prevented by low and varying contact force of tire. After the second MCR, a steering type four-wheel vehicle becomes mainstream because the tires generate the driving force and cornering force, and transmit them to the road surface certainly. In 1999 an author proposed SSM (Sensor Steering Mechanism) which was the lateral guided mechanism for a front steering vehicle, and a micom car control by SSM won the race. This year the paper about SSM was published by JSME[3].

The average speed of winners are 2.2m/s and 3.37m/s, in 1999 and 2007 MCR competition, respectively. The average speed of MCR competition improves every year. An average of 4.0m/s was recorded at a local competition in 2008. Though the layout is not same for every competition. After 2001 MCR, a special tire for MCR course surfaces was started to be used at the competition. But the tire is very simple and low cost, and generates a big cornering force and a driving force. The tire is made by a donut type sponge covered with a special silicon tape which is using by semiconductor manufacture company. The friction coefficient of this tire is over 1 by the experimental results. As a results, the micom car is able to run at high speed by the special tire and the line following method SSM.

Figure 1 shows an outside view of the 10th MCR course. The total length of the course is 66.84m. The black acrylic sheet is pasted on the course surface. The winning vehicle ran through this course in 18.86 seconds, and the average speed was 3.54 m/s. MCR regulation is explained in detail by the reference [2].

B. Technical solution of MCR

Figure 2 shows the schematic idea of SSM which is proposed by authors for the lateral guided vehicle with front steering mechanism. This figure shows a relation between an arm angle and a steering angle. Here, a steering ratio is a ratio of the arm angle and the steering angle. An arm length ratio is a ratio of the arm length and a wheel base. For a conventional SSM the steering ratio is 2 to 1, and the arm is 1. In 1999 a micom car based on this idea won the race. The average speed of this vehicle was 2.2m/s.

In order to get more speed the conventional SSM is not a suitable steering control at corners, because the slip angle of front tire becomes large at the entrance of corner. Therefore, the vehicle has to find every corner and to slow down at the entrance of them. In order to overcome this problem the modified SSM was proposed shown in Fig. 2. SSM 1:1 1L (steering ratio 1:1 and arm length ratio 1) and SSM 1:1 1.5L (steering ratio 1:1 and arm length ratio 1.5) are shown in this

Fig. 1 The 10th Memorial Event of Micom Car rally in Sapporo

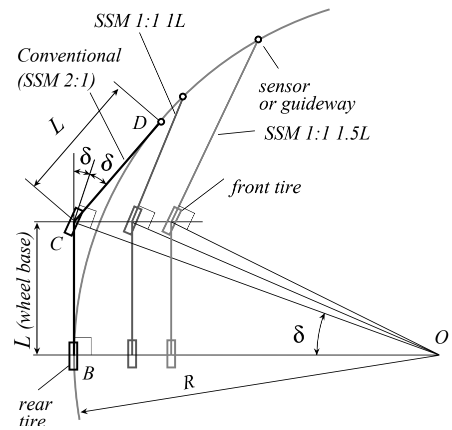

Fig.2 Schematic idea of modified SSM

figure. SSM 1:1 1.5L was applied to a 2006-type micom car which got the 2nd place at MCR competition in 2006.

In this paper the characteristics of these 2 micom cars are measured by ProReflex (Qualysis) three dimensional position measurement system which shows the problem of improvement in the speed of a micom car for the educational point of view.

C. Tires

From 2002 the running speed improved drastically by using the tire of which surface is covered with silicone tape. This paper demonstrates the speed difference with and without the silicone tape. In this case we let 1999-type car and 2006-type car run maximum speed on the 0.6m radius regular circle. The 3D measurement equipment ProReflex (Qualysis) is used to measure the running trajectory. A marker is attached to the center-of-gravity of the cars, and the locus of the point is measured optically. A turning radius and the movement speed are calculated by using output data of ProReflex. As a results the centrifugal force and the coefficient of friction obtained by the calculation are shown in Table 1. In these conditions, the centrifugal force F is balancing with a friction force, thus the friction coefficient will be set to F over mg, where g is the gravity acceleration and m is the mass of body. As a result the friction coefficient of a rubber tire is 0.59 and the silicone tape is 2.1. This value is not to be believed. There are some special relations between a silicone tape and the road surface.

D. Guiding Mechanism

In order to show the difference of guiding mechanism of SSM version, two-type of cars are run on the simple course which has a right angle, s-shaped curves and 7.348m in total length. Figure 4 shows the layout of the course and dimensions, where 0.6R means a radius of 0.6m, and 0.6L means a straight line of 0.6m. Two white lines are pasted at 1m before the right angle corner. For the 1999-type car the silicone tape is rolled around the rubber tire at this time. The running trajectory and speed are shown in Fig. 5 and Fig. 6 respectively. Here, the 1999-type and 2006-type are shown by a gray line and a solid line, respectively. 2006-type vehicle is able to run fast because SSM1:1 1.5L takes the short path at the s-shaped curve and the inside path at the corner. In figure 6, 2006-type recorded 3.6m/s at the entrance of 0.6R and the double lines before the right angle.

The size of scale ratio is 16.25 when a wheel base of real car and 2006-type micom car are 2.6m and 0.16m, respectively. Then a scale speed at 3.6m/s is 58.5m/s for the real car. In this case, the speed of real car is 210km/h at the entrance of 9.75m radius curve. As a result, MCR competition is able to experience high-speed feeling like formula one grandprix in the 0.3m width course.

E. Education and MCR

Micom car is a good mechatronics material for education. But it will need much time to win the competition. For the beginner who just begins studying for engineering at the university, much time is required to develop the micom car. In order to increase the participation of undergraduate students for MCR competition, the regulation has to change or create new competition rule on MCR course.

This paper proposes a race of inverted pendulum type robot vehicles which compete for running time on MCR course. The robot car must pass the standard MCR inspection which has specified body width, body height and tire. And the robot has to stand by the inverted controller while moving on MCR course. Nothing else exists like this competition, and an educational effect is expected through realizing an inverted control system.

III. INVERTED CONTROL VEHICLE

A. Dynamical Equations

Figure 7 shows a dynamical model of an inverted pendulum type robot vehicle PUPPY II. Here, a rigid body A is connected with two wheels which are driven by each geared motor without slip. N is a Newtonian reference frame, B is an intermediate reference frame introduced for purposes of analytical convenience, Dextral sets of mutually perpendicular unit vectors $\boldsymbol{n}_i$, $\boldsymbol{a}_i$ and $\boldsymbol{b}_i$ $(i=1, 2, 3)$ are fixed in N, A, B, with $\boldsymbol{n}_3$ is vertically upward, $\boldsymbol{b}_2$ is directed parallel to drive shafts of wheels, $\boldsymbol{a}_3$ is directed parallel to the body. M_a is a mass of body. The mass of wheel for both side are M_w. Moment of inertia in pitch and yaw axis are J_{a2} and J_{a3}, respectively. A angle of the body is θ. The rotational angle of right and left wheel are φ_r and φ_l, respectively. The tread is W. The radius of wheel is R, The control torque of right and left wheel are τ_r and τ_l, respectively. The viscous damping of both drive shaft are D. The yaw angle is γ which is calculated by φ_r and φ_l without slip of tires.

AUTOLEV is used to derive dynamical equations of motions of this model. For the simplicity, equations of motions are line-

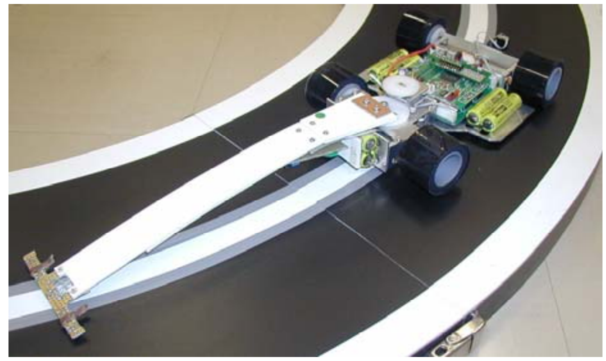

Fig. 3 Second place car in 2006 MCR

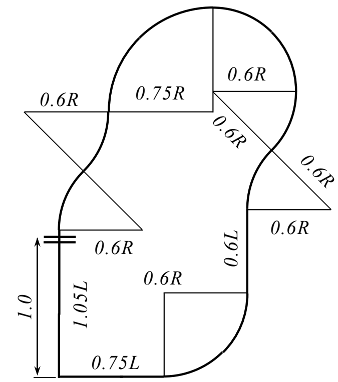

Fig.4 A test course of Micom car

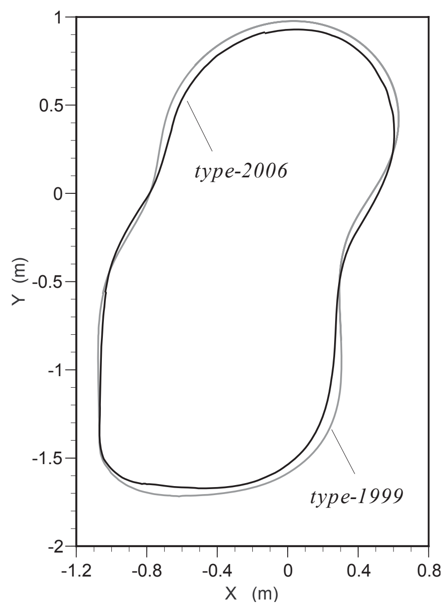

Fig. 5 Trajectory of runs

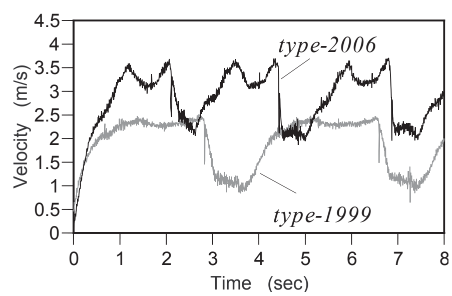

Fig. 6 Moving velocity of Micom car

arized around the equilibrium point. Obtained linearized dynamical equations of motions are shown by matrix formulation.

$$M\ddot{X} + C\dot{X} + KX = Gu \quad (1)$$

$$M = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0 & 0 \\ D & -D & 0 \\ D & 0 & -D \end{bmatrix},$$

$$K = \begin{bmatrix} k_{11} & 0 & 0 \\ k_{21} & 0 & 0 \\ k_{31} & 0 & 0 \end{bmatrix}, \quad G = \begin{bmatrix} 1 & 1 \\ 0.75 & 0.25 \\ 0.25 & 0.75 \end{bmatrix}, \quad u = \begin{bmatrix} \tau_r \\ \tau_l \end{bmatrix}$$

Here, a mass matrix, a damping matrix, a stiffness matrix, a force matrix and a input vector are M, C, K, G and u, respectively. A displacement vector is as follows:

$$X = [\theta \ \ \varphi_r \ \ \varphi_l]^T. \quad (2)$$

Element of M and K matrix are as follows:

$$m_{11} = -\{Ja_2 + 2M_wR^2 + M_a(L+R)^2\}$$

$$m_{12} = m_{13} = -\frac{1}{2}R\{M_a(L+R) + 2M_wR\}$$

$$m_{21} = -\frac{1}{2}R\{M_a(L+R) - 2M_wR\}$$

$$m_{22} = m_{33} = -\frac{1}{4}\{\frac{5}{2}M_wR^2 + 4Jw_2 + M_aR^2 + \frac{R^2}{W^2}(2Jw_3 + Ja_3)\}$$

$$m_{23} = m_{32} = -\frac{3}{16}R^2\{2M_w + \frac{4}{3}M_a - \frac{4}{3W^2}(Ja_3 + 2Jw_3)\}$$

$$m_{31} = -\frac{1}{4}R\{2M_a(L+R) + 4M_wR\}$$

$$k_{11} = 2M_wgR + M_ag(L+R)$$

$$k_{21} = k_{31} = \frac{1}{2}M_agR + M_wgR.$$

B. Control System Design

In order to translate the dynamical equation to a state equation, the state variables are selected as follows:

$$x = [X^T \ \dot{X}^T]^T = [\theta \ \ \varphi_r \ \ \varphi_l \ \ \dot{\theta} \ \ \dot{\varphi}_r \ \ \dot{\varphi}_l]^T \quad (3)$$

and the state equation is as follows:

$$\dot{x} = Ax + Bu \quad (4)$$

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ M^{-1}G \end{bmatrix}. \quad (5)$$

In equation (1), the 2nd and 3rd column elements of K are zero. If φ_r and φ_l are removed from the state variable x, the system does not change. As a result, a new state variable becomes as follows:

$$x = [\theta \ \ \dot{\theta} \ \ \dot{\varphi}_r \ \ \dot{\varphi}_l]^T. \quad (6)$$

At the same time, the 2nd and 3rd column and raw elements are able to remove from A matrix. The 2nd and 3rd raw elements are also removed from B matrix. The new system is not influenced by the wheel rotational angle φ_r and φ_l. Reference documents of PUPPY II are not found. There is a instruction manual[12] and report of PUPPY (Hokuto Denshi Corp.)[13] which is a former model of PUPPY II and is an inverted pendulum robot vehicle with one wheel drive motor. In this paper, the control method of PUPPY described in reference [12] and [13] is applied to the stabilization of PUPPY II. This paper does not describe a detailed theory, because it can derive by application of references.

C. Line following control of PUPPY II

The control program of PUPPY II is able to develop by using

Table 1 Steady state turning on circle

	1999-type	2006-type
Radius of rotation (m)	0.646	0.560
Moving speed (m/s)	1.93	3.40
Mass of body m (kg)	1.287	0.596
Centrifugal force (N)	7.42	12.30
Friction coefficient F/mg	0.588	2.104

Table 2 Experimental results of test running

	1999-type	2006-type
Distance (m)	7.348	
Lap (sec)	3.72	2.29
Mean speed (m/s)	1.98	3.21

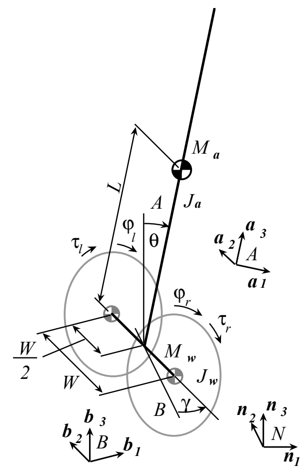

Fig. 7 Dynamical model of two-wheel inverted pendulum type vehicle

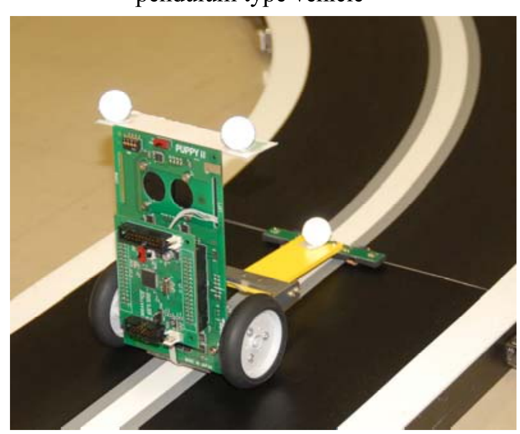

Fig. 8 Outside view of PUPPY II with line sensor

accessory tools the same as PUPPY. But the control circuit of PUPPY II is different from PUPPY. It is necessary to revise a sample program of PUPPY to PUPPY II. In order to develop the control program, programmers require the knowledge of microprocessor hardware. This paper describes the method of line trace after the inverted stabilization of PUPPY II.

Figure 8 shows an outside view of PUPPY II with line sensors for line following. In order to sense in front of the body, a sensor array is attached at top of the arm which is able to freely rotate driving shafts through bearings. Five reflection type photo interrupter GP2S05(Sharp) are used to follow the gray line for 2 sensors, to find white line for 2 sensors and to find end of center line for a sensor. For the line trace two sensors are located over the edge of gray line of which width is 40mm. Following sensors outputs are leaded to AD port of CPU and others are connected with digital input port.

Figure 9 shows an experimental data of line following sensors output when the sensor array moves over gray line left to right. Here, the emitter and corrector of GP2S05 are connected to the ground and the power line through resister, respectively. In this figure, a difference of the left and right sensors output is shown. As a result, this difference gives a liner control input for line following around the center line.

IV. VERIFICATION BY EXPERIMENT

A. Control system

Figure 10 shows the constructed control system for PUPPY II. A Control CPU is SH7125 (Renesas Technology Corp.) with inputs sensor outputs and control DC motor by PWM (Pulse Width Modulation). For the experiment, the sensor array and sensor arm are attached to PUPPY II. The control program is edited and compiled by a personal computer and downloaded to EEPROM and executed by CPU.

Figure 11 shows a control block diagram of inverted pendulum type vehicle. Here the stabilization of inverted control is realized by state feedback gains $\boldsymbol{F}$ which are derived by the described theory. The line following control is executed by following; the yaw angle of the body is sensing by the difference of line following sensors outputs, and target values of rotational speed of each wheel are varied. K_p is obtained by experimentally.

B. Derivation of State feedback Gains

Derivation of state feedback gains of the control system are described by using expanded discrete time state variables as follows:

$$\boldsymbol{x}_d(k)=[\theta\ (k)\ \ \dot{\theta}\ (k)\ \ \dot{\varphi}_r(k)\ \ \dot{\varphi}_l(k)\ \ \sum_{i=0}^{k-1}\dot{\varphi}_{rd}(k-1)-\dot{\varphi}_r(k-1)$$
$$\sum_{i=0}^{k-1}\dot{\varphi}_{ld}(k-1)-\dot{\varphi}_l(k-1)\ \ \tau_r(k-1)\ \ \tau_l(k-1)\ ]^T \qquad (7)$$

Here, k is the sampling interval of this control system. The 5th and 6th element of equation (4) are the summation of velocity errors which are shown by integration block in Fig. 11. Table 2 shows physical parameters of PUPPY II. These values are applied to the equation (1) and obtained values are as follows:

$$\boldsymbol{M}=\begin{bmatrix} -0.003521130 & -0.00037366500000 & -0.00037366500000 \\ -0.000373665 & -0.00009711282091 & -0.00004663512793 \\ -0.000373665 & -0.00004663512793 & -0.00009711282091 \end{bmatrix}$$

$$\boldsymbol{C}=\begin{bmatrix} 0 & 1.0\times10^{-4} & 1.0\times10^{-4} \\ 0 & -1.0\times10^{-4} & 0 \\ 0 & 0 & -1.0\times10^{-4} \end{bmatrix} \quad \boldsymbol{K}=\begin{bmatrix} 0.25280370 & 0 & 0 \\ 0.04694085 & 0 & 0 \\ 0.04694085 & 0 & 0 \end{bmatrix}. \qquad (8)$$

These values are applied to a equation (5), and reduced state variables equation (6) are calculated as follows:

$$\boldsymbol{A}=\begin{bmatrix} 0 & 1.0 & 0 & 0 \\ 5.551718201234 & 0 & 0.228031504658 & 0.228031504658 \\ 312.118312512663 & 0 & -1.931123137163 & 0.049949968690 \\ 312.118312512663 & 0 & 0.049949968690 & -1.931123137163 \end{bmatrix}$$

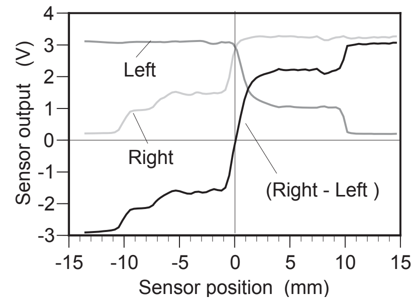

Fig. 9 Sensor outputs and difference

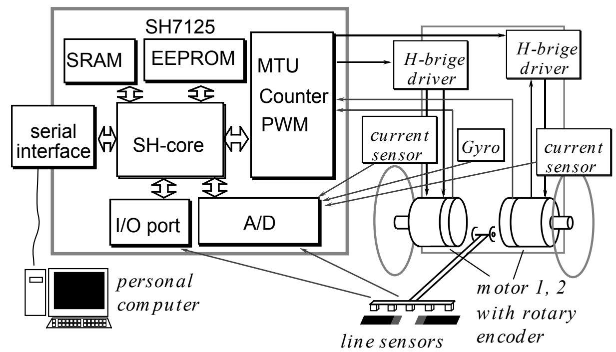

Fig. 10 Control system for PUPPY II

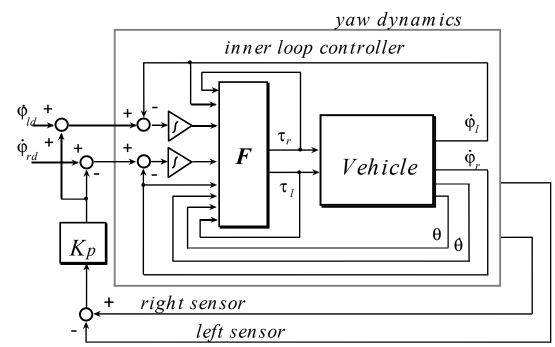

Fig. 11 Block diagram of line trace for inverted pendulum type vehicle

$$\boldsymbol{B}=\begin{bmatrix} 0 & 0 \\ 1013.2782962037 & 1013.2782962037 \\ -11064.9552642121 & -1159.5897349491 \\ -1159.5897349491 & -11064.9552642121 \end{bmatrix}. \qquad (9)$$

Here the continuous time system is translated to the discrete time by 10ms time interval. Forward difference operator is applied to these equation and expanded equations obtained. By using obtained equations, LQ (linear quadratic optimal control) gains are calculated by using weight square matrix $\boldsymbol{Q}$ and $\boldsymbol{R}$. Here, $\boldsymbol{Q}$ is a unit matrix, $\boldsymbol{R}$ is a diagonal matrix of which elements are set at 0.55×10^8. As a result state feedback gain $\boldsymbol{F}$ are calculated as follows:

$$\boldsymbol{F}=\begin{bmatrix} 0.34360841411007 & 0.34360841410998 \\ 0.04927803508676 & 0.04927803508675 \\ 0.00205155850460 & 0.00362648095871 \\ 0.00362648095871 & 0.00205155850459 \\ 0.00000444095378 & -0.00012094048878 \\ -0.00012094048878 & 0.00000444095378 \\ 0.21835861946870 & 0.07334460971747 \\ 0.07334460971748 & 0.21835861946868 \end{bmatrix}^T. \qquad (10)$$

Control torques are obtained by gain matrix $\boldsymbol{F}$ times state variables $\boldsymbol{x}_d$.

C. Experimental Results

The stabilized inverted program is developed, downloaded to EEPROM and executed on PUPPY II shown in Fig.7. A course for the experiment is constructed with 0.75mm and 0.6m radius curves and a right angle corner are connected with straight lines. Moving trajectory of PUPPY II is took by ProReflex while running on this course. Then three reflectable markers are attached at a left and right top of the body and a center of sensor array. Figure 12 and 13 show moving trajectory and velocity of markers attached to the robot. Figure 12 shows that the sensor array is following the line, when the vibration is remaining small enough. At the right angle corner, the robot makers left turn and returns to line trace mode by using dead reckoning when the robot finds right angle corner to the left. The oscillating damping characteristic is satisfactory in this speed. Figure 13 shows moving speed of markers, here the speed is recorded at 0.13m/s. There are some abilities to move fast by doing research of control algorithm and revising control system and mechanism. The competition of time by the inverted pendulum type robot vehicle on MCR course is new and challenging.

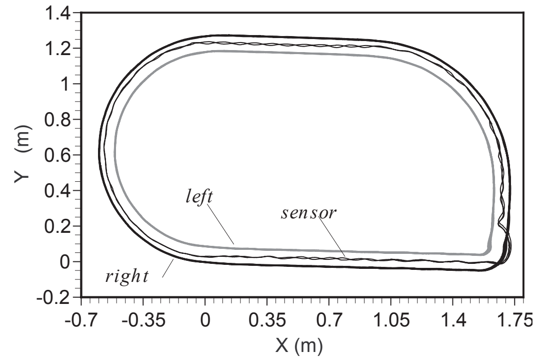

Fig. 12 Moving trajectory of PUPPY II on the test course

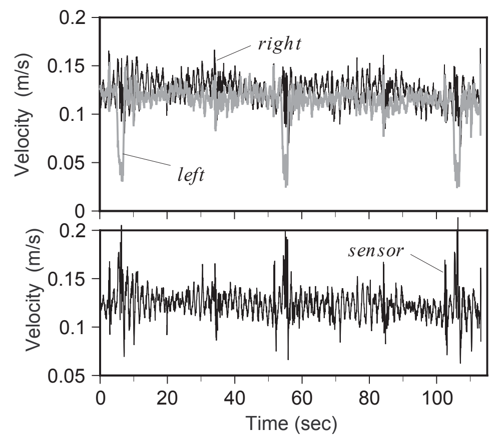

Fig. 13 Moving speed of run

Table 3 Physical parameter of PUPPY II

mass of body Ma [kg]	*0.27*
mass of wheel Mw [kg]	*0.03*
moment of inertia Ja2 ,Ja3 [kgm2]	*1.332×10^{-3}*
moment of inertia Jw2 , Jw3 [kgm2]	*4.983×10^{-6}*
mass center to axle L [m]	*0.06*
tread W [m]	*0.12*
gravity acceleration g [m/s2]	*9.81*
damping facter D [Nm s]	*1.00×10^{-4}*
radius of tire R [m]	*0.029*

V. CONCLUSIONS

The authors recommended the participation of robot contest to young engineers, because the microcomputer control technique is able to learn while making own robot car, developing the control program and enjoying the race. In recent years the improvement of moving speed of micom car is remarkable. MCR is kept at distance by beginners who are undergraduate students in engineering course. Thus it should revise the rules or create new rules for undergraduate students. This paper proposes the new race in MCR competition by time for inverted pendulum robot vehicle which is able to control by a low cost and small MEMS gyro. As an example, the stabilized control system and line following method are described for a commercially developed inverted control robot vehicle PUPPY II. Experimental result shows that PUPPY II is able to turn on MCR course smoothly. The competition of tine by the inverted pendulum type robot vehicles on MCR course is new and challenging. We need to request to hold this race for the organizer of MCR competition.

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