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Development of the Two-Wheeled Inverted Pendulum Type Mobile Robot WV-2R for Educational Purposes

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Abstract—**The rapidly increase of personal robotic platforms and their applications in Japan represents a great challenge for universities to introduce undergraduate students the basic knowledge required to develop intelligent automated mechanisms. For this purpose; in this paper, we are presenting our approach to introduce first year undergraduate students of the Department of Modern Mechanical Engineering the basics of robotics systems. In order to foster the creativity of undergraduate students of engineering fields, we focused in developing an education tool designed to introduce at different educational levels the principle of developing mechatronic systems. In particular, the development of an inverted pendulum mobile robot Waseda Wheeled Vehicle No. 2 (WV-2R) has been proposed. Different kinds of experiments were proposed to confirm the possibility of implementing controllers as well as changing physical properties of the system to observe differences on the response of the system. From the experimental results, we could confirm the effectiveness of the proposed systems to control the angle of pendulum respect to the body base as well as by changing the radius of the wheel.**

I. INTRODUCTION

Japan as one of the leading nations in scientific research and production of innovative technological products, it holds very large shares in high-technology industries such as electronics, robotics, industrial chemicals, machine tools, electronic media and so on. As a result from several decades of research, Japan has contributed to the industrial development, principally in the field of chemicals, metals, semiconductors, robotics, entertainment, machinery, industrial robotics and optics. It is also one of the leading nations in health care and medical research and robotics.

In particular, in the robotics field, Japan is one of the premier designer and producer of robots in the world, having created a number of entertainment and industrial robotics through commercial production and research. Such kind of unique environment has been possible thanks to the great contribution and dedication from universities and private corporations.

Such great efforts have been of vital importance for the introduction of robots in different application purposes such as industrial [1, 2], entertainment [3, 4], personal use [2], welfare [5, 6], education [7, 8, 9, 10], rehabilitation [11], etc. In addition, the constant support from the Japanese government has motivated the rapid increase of Japanese companies and academic institutions related to robotics field. In fact, the Japan Robot Association [12], a trade group which promotes the use of robot technology, expects the Japanese market for next-generation robots (including personal robots) to reach $14 billion by 2010 and more than $37 billion by 2025 [13]. As a consequence, the Japanese government strongly believes that robotics will constitute a strength key of the Japanese economy in the future decades.

However, the continuous falling of the birthrate in Japan is resulting in a reduction in the number of students where most of them are going away from scientific fields. This situation may tremendously affect the Japanese industry by losing its international technological competitive power in the future due to the shortage of talented engineers. Moreover, the curricula of engineering universities is currently lacking in practical, design elements resulting in a shortage of opportunities for promoting the creativity of students.

From the academic point of view, the issues described above, it represents a great challenge for universities to motive them to get involve in the robot technology by introducing in simple and efficient ways the basic components of robots as well as their application for solving real-world problems. In recent years, the proliferation of amateur robot contests (including elementary school children) supported by private companies and local governments (i.e., Rescue-Robot Contest [14], Japan Robot-Sumo Tournament [15], etc.) has been demonstrated an effective way of motivating them to get involve in the robotics field. Such kind of contests represents an opportunity for students to actually create an object by themselves to enhance their understanding of robot technology, cultivate their practical abilities and strive enthusiastically to achieve higher levels of accomplishment.

Therefore, in this paper, we focused on implementing the Project-based learning (PBL) to the introductive course of mechatronics to 1st year undergraduate students of the Department of Modern Mechanical Engineering at Waseda

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University. Project-based learning (PBL) is a model that organizes learning around projects. According to the definitions found in PBL handbooks for teachers, projects are complex tasks, based on challenging problems that involve students in design, problem-solving, decision making. Such kinds of issues give students the opportunity to work relatively autonomously and culminate in integrating a complete system ([16], [17]). This diversity of defining features coupled with the lack of a universally accepted model or theory of Project-Based Learning has resulted in a great variety of PBL research and development activities. This variety presents some problems for a research review. Moreover, the influence of the cultural background of students may complicate the implementation of efficient strategies to foster their creativity while solving problems.

In this paper, we focused in presenting our approach towards developing an education tool designed to introduce at different educational levels the principle of developing mechatronic systems. In particular, the development of an inverted pendulum mobile robot has been proposed. As a first approach, the proposed system has been designed to be implemented within the Mechatronics Laboratory (2) which is taken by 1st year students of the Modern Mechanical Engineering Department at Waseda University. This paper is organized as follows: the details of the first robot's prototype are presented. Then, the design of the Waseda Wheeled Vehicle No. 2 Refined (WV-2R) is detailed. Finally, a set of experiments are proposed to verify the effectiveness of each of the proposed mechatronic systems.

II. RESEARCH BACKGROUND

In the recent years, in order to foster the creativity of undergraduate students of engineering fields, the acquisition of technical skills requires an interdisciplinary approach to understand the basic knowledge among different backgrounds such as: advanced programming, peripherals devices and dynamic system control, real-time control, simulation analysis, etc. As an approach to cover different aspects of the Robot Technology, in this project, we focused in developing an education tool designed to introduce at different educational levels the principle of developing mechatronic systems. In particular, the development of an inverted pendulum mobile robot has been proposed.

In fact, the inverted pendulum has been the subject of numerous studies in automatic control [18-21]. From the perspective of introducing RT technology to undergraduate students, it is a good example to provide experience to them on control design, signal processing, distributed control systems and the consideration of real-time constraints for real applications purposes.

Last year, we have developed the Waseda Wheeled Vehicle No. 1 (WV-1), as is shown in Fig. 1. The WV-1 is composed by a two-wheeled mobile base, two DC motors, a microcontroller (distributed by ST Microelectronics [23]) and sensors (Table I). The control diagram of the WV-1 is shown in Fig. 2; where a remote controller has been included in order to enable students to control the motion of the robot.

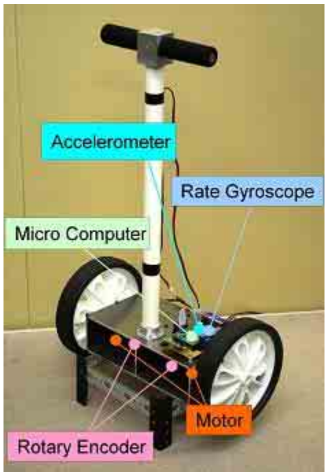

Fig. 1 Screenshot of the first prototype of the inverted pendulum's mobile robot WV-1.

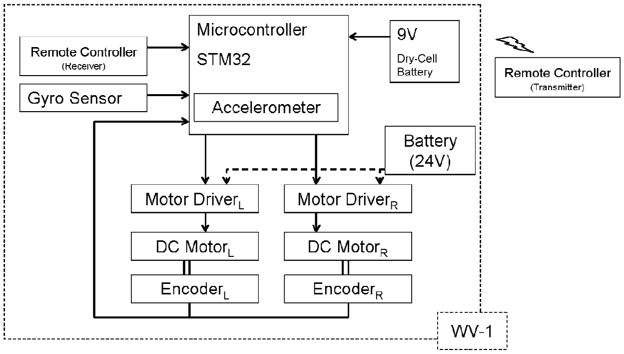

Fig. 2 System diagram of the WV-1.

TABLE I
SPECIFICATIONS OF THE WV-1

Parameter	Specifications
Height	660 mm
Weight	4.9 kg
Motor	DC Servo Motor
Power Consumption	90 W
CPU	STM32F103VB (72 MHz)

III. WASEDA WHEELED VEHICLE NO. 2 REFINED

A. Design Concept

As it was previously introduced, it is important to introduce the basic concepts of Robot Technology, not only to undergraduate students but also junior high school students. For this purpose; in this year, we have proposed the development of the Waseda Wheeled Vehicle No. 2 Refined (WV-2R). The design concept of the WV-2R (Figure 3) was based on the principles of improving the following key issues of the prototype WV-1: compact design; safety measures, educational issues.

Regarding the first issue, we have decided to select low-cost hardware components which fit to the required specifications as shown in Table II. Regarding the second issue, safety measures have been considered to avoid any possible risk to the student as well as assuring its durability after several experiments (not to break down easily). Finally, we consider specific design issues to enable students to practice several principles of robotics as well as control theory such as modifying the center of mass etc. In that way, students may have hand on experience with the WV-2R.

B. Inverted Pendulum Modeling

The pendulum system has an arm that swings in the horizontal plane, driven by a DC motor. The purpose of the arm is to provide a balancing torque to a swinging pendulum to keep the pendulum in an upright position. The angle of both the arm and pendulum is monitored and used as feedback to control the motion of the system. The model description is shown in Figure 4; where the following parameters are defined as follows:

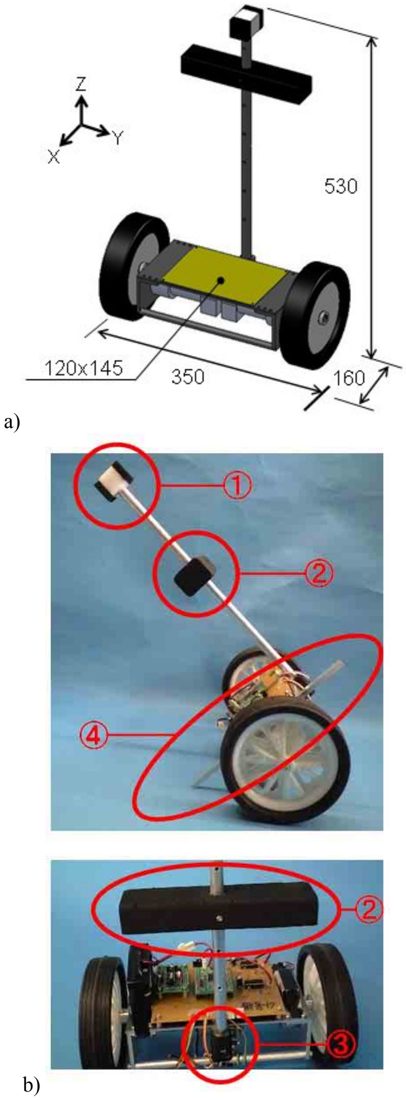

Fig. 3 System overview of the Waseda Wheeled Vehicle No.2 Refined (WV-2R) developed for education purposes: a) 3D system diagram; b) designed functions: ① (cushioning material to avoid any possible damage of the robot while falling down during an experiment); ② (weighting bar); ③ (installation mechanism to block of the shaft) and ④ (stand shaft to avoid any possible impact with the ground)

θ	Body Inclination
ϕ	Wheel Angular Velocity
m_1	Body Weigh
m_2	Wheel Weight
J_1	Body Moment Inertia
J_2	Wheel Moment of Inertia
l	Distance between the wheel axis and the center of mass
r	Wheel radius

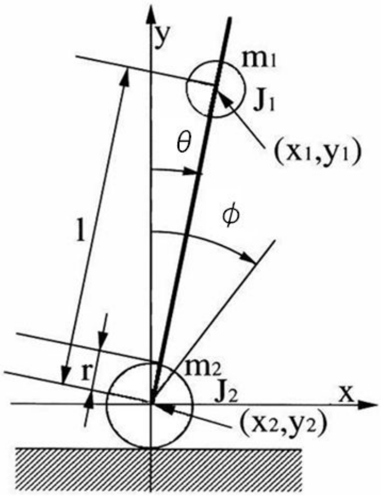

Fig. 4 Diagram model of the Inverted Pendulum.

TABLE II
WV-2R REQUIRED SPECIFICATIONS

Property	Specification
Height [mm]	530
Weight [kg]	3.2
DOFs Configuration	2-DOF

By using the above parameters, and by defining *T* as torque, *n* as Reduction Gear Ratio and *S* as the Frictional Force on the wheel along the horizontal ground plane, we may define the following relations:

$$m_2 x_2'' = S - f_x \tag{1}$$

$$J_2 \phi'' = nT - rS \tag{2}$$

$$m_1 (x_2'' + (l \sin\theta)'') = f_x \tag{3}$$

$$m_1 (l \cos\theta)'' = -m_1 g + f_y \tag{4}$$

$$J_1 \theta'' = f_y l \sin\theta - f_x l \cos\theta - nT \tag{5}$$

$$x = r\phi \tag{6}$$

$$\theta'' = \frac{1}{J_1 + m_1 l^2 + \dfrac{{m_1}^2 r l^2 \cos^2\theta}{\dfrac{J_2}{r} + rm_1 + rm_2}} \left[m_1 g l \sin\theta - m_1 l \cos\theta \left\{ \frac{nT + m_1 r l \theta'^2 \sin\theta}{\dfrac{J_2}{r} + rm_1 + rm_2} \right\} - nT \right] \tag{7}$$

$$\phi'' = \frac{1}{J_2 + r^2 m_1 + r^2 m_2} \left\{ nT - m_1 r l (\theta'' \cos\theta - \theta'^2 \sin\theta) \right\} \tag{8}$$

From the Eq. (7), when the angular acceleration of the body is less than zero, it is possible to correct the vertical inclination of the body to the standing upright position. Consequently, if we assume that the angular velocity on Eq. (4) is equal to zero, the angular acceleration is less than zero, so that it is possible to compute the maximum inclination angle of the body. In our case, by substituting the corresponding values, the limit inclination angle that WV-2R is able of controlling is 70°.

C. Control System Implementation

In Fig. 5, the block diagram of the control system implemented for the WV-2R is shown. As we may observe, the inclination of the body of the WV-2R is controlled by a PD controller. In particular, the body inclination angle is θ determined from the measured data from the accelerometer, the angular velocity is determined from the rate gyro sensor data, the wheel acceleration ϕ' is obtained by collecting the data from the encoder attached to each of the motors of the WV-2R. By considering computing the body inclination by means of θ and θ' and the offset position of the robot by means of ϕ and ϕ' $(\theta=\theta'=\phi=\phi''=0)$; it is possible to compute the required output voltage to assure the stability of the inverted pendulum of the robot by computing Eq. (9). In particular, $K_1 \sim K_4$ parameters are the gain coefficients of the controller which are tuned to assure the stabilization of the system.

$$V_{out} = k_1 \cdot \theta + k_2 \cdot \theta' + k_3 \cdot \phi + k_4 \cdot \phi' \qquad (9)$$

There are two main reasons why the body inclination angle θ is measured by means of two sensors. The first reason is that the accelerometer can measure the body inclination angle by recording the gravitational force; however, it is not possible to measure the inclination angle θ with high accuracy in short term (the translation angular velocity is also taken into account). On the other hand, in order to compute the inclination angle θ by the rate gyro, it is required to perform an integration of the sensor signal; which it accumulates errors in a long term. As a result, we have combined both sensor information to improve the accuracy of the measurement of the inclination angle by applying a low-pass filter to the accelerometer signal and a high-pass filter to the integration value from the rate gyro signal.

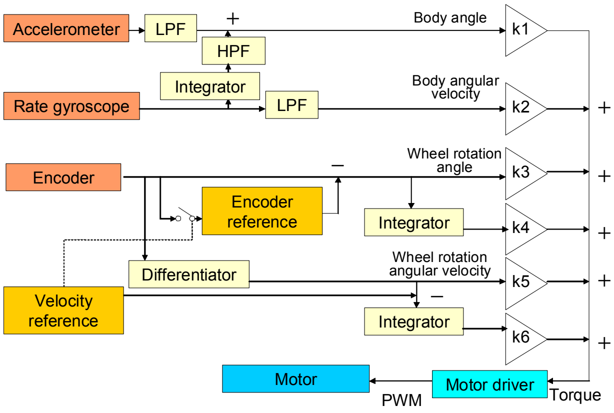

Fig. 5 Block Diagram of the Control System of WV-2R.

IV. EXPERIMENTS & RESULTS

A. Detection Accuracy of the Inclination Angle

In this experiment we focused in determining the accuracy of the detection of the body angle of WV-2 computed from the sensors attached to the mechanism. In order to avoid the accumulation of the detection of the offset of the pendulum, we have combined the data collected both from the accelerometer and rate gyro sensors. From the data obtained through the rate gyro sensor, the inclination of the pendulum can be computed by computing its integral over time. Moreover, the noise of the accelerometer sensor was removed by applying a low-pass filter. The delay caused by the low-pass filter was compensated by implementing a high-pass filter on the integral of the rate gyro sensor data. In order to verify the effectiveness of the detection of the pendulum angle respect to the body, we have programmed the robot to maintain an inclination of 45 degrees and then slowly go down. During this experiment, we have registered the information collected through the each of the sensors as well as the combined data as it was previously proposed. The experimental results are shown in Fig. 6. As we may observe, when both data collected from the accelerometer and the rate gyro are combined, the angle of the pendulum is smoothly

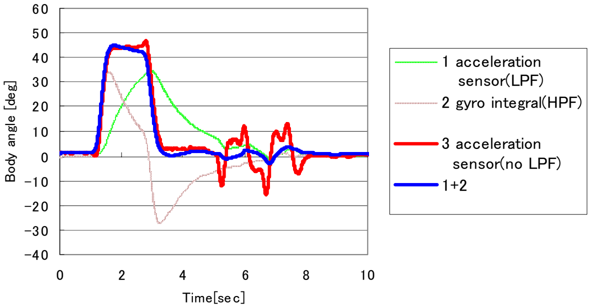

Fig. 6 Experimental results while programming WV-1 to go slowly from a vertical position to an inclination of 45 degrees.

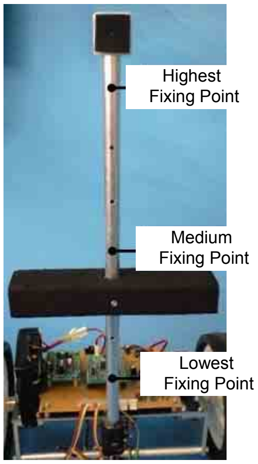

Fig. 7 Experimental conditions while varying the location of the weighting bar (1kg)

measured. Thanks to this result, we may assure that undergraduate students may able of understanding with the WV-1 the principles of sensor signal processing.

B. Changing the Center of Mass

In this experiment, we focused in determining the differences on the control parameters of the WV-2R when the weighting bar is placed in difference locations, as it is shown in Fig. 7. For this purpose, we have programmed the robot to keep a constant inclination angle of 30^o so that the gain parameters of controller K1 and K2 are tuned to assure the stability of the pendulum of the WV-2R. The experimental results are shown in Table III. As we may observe, a higher gain value is required when the weighting bar is placed in the highest location. This is because a higher level of torque is required to compensate the moment as the center of gravity is changed (of course, the moment of inertia is as well increased). From these results, we may assure that students may able of understanding the factors that may affect the stability of the control system while doing real experiments (not only through simple simulation).

C. Changing the Dimensions of the Wheel

In this experiment, we have focused in confirming the dynamical changes on the control parameters of the WV-2R while modifying the diameter of the wheel. Similar to the previous experiment, the WV-2R was programmed to keep a constant inclination angle (30^o) while tuning the gain parameters of the controller up to assuring the stability of the system. In particular, two wheel dimensions were tested for *r*: 160mm and 200mm (Figure 8). The experimental results are shown in Table IV. As we may observe, the when the dimension of the wheel is increased a higher value of the gain parameters of the controller are required. This is mainly because a higher torque is required to compensate the moment of inertia due to increase of frictional forces respect to the ground.

TABLE III
EXPERIMENTAL RESULTS WHILE TESTING DIFFERENT POSITIONS OF THE WEIGHTING BAR

Weight Location	Distance between the wheel axis and the center of gravity mm	Moment of Inertia $J_1 \times 10^4$ Kg·mm^2	Proportional Gain k_1	Derivative Gain k_2
Highest Rung	80	5.3	0.8	0.1
Middle Rung	50	2	1.2	0.11
Lowest Rung	30	1	0.6	0.08
No Weight	20	0.5	0.5	0.06

TABLE IV
EXPERIMENTAL RESULTS WHILE TESTING DIFFERENT DIMENSIONS OF THE WHEEL

Wheel Radius r [mm]	Mass m_2 [kg]	Moment of Inertia $J_2 \times 10^4$ [Kg· mm^2]	Proportional Gain k_1	Derivative Gain k_2
160	0.8	0.03	1.2	0.11
200	0.96	0.48	1.5	0.14

D. Field Experiment

As a first approach, in order to determine the effectiveness of using the proposed system to introduce robotics principles to students, six high school students were asked to assemble the components of the WV-2R (Figure 9). All of them didn’t have any experience with any kind of robotic platform. The procedure of the experiment is as follows: at first a short introduction lecture of robotic has been given. Then, subjects were asked to assemble the parts of the WV-2R by following a manual prepared beforehand the experiment. Finally, they could able of testing the robot by using a remote controller. After they were able of doing some experience with the functions of the WV-2R, they were asked to compile a questionnaire.

Fig.8 Experimental conditions while varying the dimensions of the wheel dimensions on the WV-2R.

The questionnaire basically request from subjects to give their impressions about the WV-2R, about the task assigned (assembly of the robot) and about the level of understanding regarding the components of the robot and control principles. The results are shown in Fig. 10. As we may observe, most of the students could get the idea about the components of Mechatronics systems as well as the basic idea of control theory. Finally, the five students have expressed that the proposed experiment with the WV-2R make them to have more interest on the deeper understanding robot.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we have presented our approach to introduce undergraduate students the principle of Mechatronics and Robot Technology by developing two-wheeled mobile inverted pendulum. In particular, we have detailed the development of the Waseda Wheeled Vehicle No.2 Refined (WV-2R) which it has been designed to introduce basic knowledge of control theory to undergraduate students. As a result, the WV-2R has been designed to enable students to verify the changes on the response of the robot while varying some physical parameters of the robot. A set of experiments were proposed to verify if the proposed design of the WV-2R may or not provide practical experience to students while implementing a PD controller as well as while varying

Fig. 9 Photographs taken during the field experiment was held with high-school students from Fukuoka Prefecture in Japan

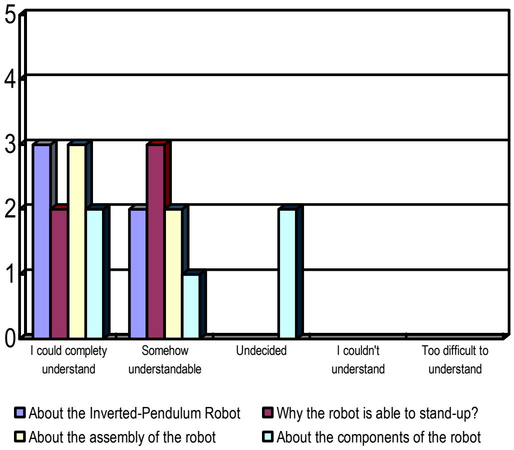

Fig. 10 Results of the questionnaire given to the students after the practical session with the WV-2R

different physical parameters of the robot, such as: center of mass and dimensions of the wheel. From the experimental results, we could confirm the effectiveness of the proposed system.

As a future work, different kinds of sensors will attached to the robot in order to implement other kinds of practical experiments as well as other kinds of robot contest (i.e. line following, soccer, etc.). As basic experiments, we have tested the WV-2R to perform simple soccer games, line tracing, etc.

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