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Development of a mobile robotic cart to support HOT patient's going out via Force and Inverted pendulum control

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***Abstract*— Home Oxygen Therapy (HOT) patients must take the conveyance cart to carry oxygen equipment when they go out. However the equipment is heavy enough to discourage the patients from going out. Therefore, in this study, we attempt to develop a mobile robotic conveyance cart to support HOT patient's going out by applying Force control and Inverted pendulum control which can also prevent the falling over of the cart. In this paper, we describe the control principle of Force control with Inverted pendulum control by several dynamical simulations, and we also show the effectiveness of our proposed control system by several experiments.**

Keywords—Home oxygen therapy; Mobile robotic cart; force control; Inverted pendulum control

I. INTRODUCTION

Home oxygen therapy (HOT) is a medical treatment for the patients who suffer from lung trouble such as chronic obstructive pulmonary disease (COPD), and it is assumed about 160,000 patients are under the HOT treatment Japan [1].

HOT patients always need to receive highly -concentrated oxygen to keep the level of oxygen in the blood, so the patients must carry a portable oxygen tank when they go out as shown in Fig.1. And especially COPD patients are recommended to get moderate exercise, i.e. walking outdoors, to maintain their physical strength, so they have to use portable oxygen equipment. However the mass of portable oxygen equipment, which includes a portable oxygen tank, oxygen saver (which means a flow controller), and carry cart, becomes about 5 kg in total. Thus the mass is heavy enough to prevent the patients from going out.

According to a questionnaire survey to HOT patients, 55 respondents (effective number of the answer is 88) answered that the reason of avoidance from going out is a problem of portable oxygen equipment. For more detail, 36 respondents who answered the previous question also answered that the weight of the portable oxygen equipment is a problem (effective number of the answer is 53) [2].

In such background, we have been proposed and developed mobile robot prototypes to carry the oxygen equipment by following HOT patients. And we also have shown the effectiveness of the mobile robotic cart to support carrying portable oxygen equipment by several user tests [3] [4] [5].

In this study, we attempt to develop a new type of mobile robotic cart which applies Force control including Inverted Pendulum control system to decrease the burden of HOT patients. As HOT patients need to breathe highly-concentrated oxygen, they always have to be connected to oxygen apparatus through the cannula tube. Therefore they feel secure to know that they are always connected to the oxygen apparatus when they hold the rigid handle of robotic cart. Addition to it, the mobile robotic cart is preferred to be easy and intuitive to control such as commonly-used wheeled carry-on cart.

For the above mentioned reasons, our proposed mobile robotic cart applies lightweight and rigid structure controlled by direct handling same as commonly-used wheeled carry-on cart. Then, for the purpose of reducing cost and weight of the robotic mobile cart, we use only one DC motor and differential gear set to drive the robotic mobile cart. Reducing mechanical parts' number probably contributes to improve the mechanical system's reliability, so the structure probably contributes to improve the reliability of our proposed robotic cart, too. Of course, one DC motor and differential gear set allows the robotic cart drive actively and turn passively, so the usability of the robotic cart keeps high level.

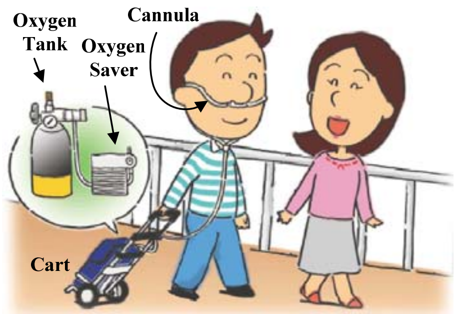

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Fig.1 HOT patients always take a set of portable oxygen equipment when they go out. They are always connected to the oxygen equipment by cannula tube to supply the highly concentrated oxygen. Whole mass of the oxygen equipment is heavy enough to discourage the patients from going out.

In this paper, we describe the design of our proposed mobile robotic cart, control principle and its performance by several dynamical simulations. Then we introduce actual mechanical design and its effectiveness by several experiments via a prototype robotic cart.

II. POWER ASSIST PRINCIPLE AND PROCEDURE

A. *Power Assist by Inverted Pendulum Control*

We describe the control principle of the mobile robotic cart. When HOT patient hold and pull the handle of the mobile robotic cart, it leans to the patient's side and moves forward to reach the equilibrium point to keep its attitude by means of Inverted pendulum control as shown in Fig.2.

Addition to straight going property described above, turning property of the mobile robotic cart is also important. Major past researches on Inverted pendulum control needed two driving wheels for its locomotion, however, here we propose the concept of the robotic cart, with low cost and without complicated sensor fusion. Therefore we try to realize "passive turning" by applying a differential gear mechanism for its actuation to achieve our concept. [4]

B. *Attaching Force Control to Inverted Pendulum Control*

There are several problems to operate our proposed robotic cart by applying Inverted pendulum control. The velocity of the robotic cart is calculated by its inclination angle because the robotic cart applies Inverted pendulum control. Therefore, after fixing the geometric relation between the user and robotic cart, the velocity of the robotic cart is also fixed. However the robotic cart needs to change its velocity in the situation of fixing its inclination angle in fact. Addition to it, feedback gains for the inclination angle and angular velocity of the controller are reduced to decrease the sensitivity of inclination angle when users hold and operate the mobile robotic cart. This feedback gain reduction produces a kind of time lag when the users operate the robotic cart. We therefore propose to apply Force control system to improve the operational usability as shown in Fig.3.

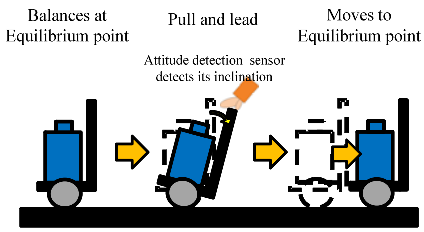


Fig.2 Power assist principle of the mobile robotic cart by applying Inverted Pendulum control .

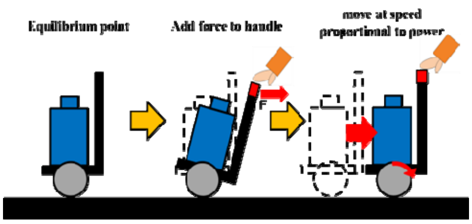


Fig.3 New power assist principle of the mobile robotic cart by applying Force control attached to Inverted Pendulum control

C. *Mechanical passive turning operation*

As described in section I, we use only one DC motor and differential gear which are set to drive the robotic cart to reduce the mechanical parts number and to improve the cost performance and the reliability of the mechanical system. This is because that the structure allows the robotic cart to drive actively and turn passively. The structure keeps the usability of robotic cart high level.

Fig.4 shows overview of the robotic cart and construction of its actuation mechanism. There is one DC motor with planetary reduction gear which is connected to the ring gear of differential gear set. Two drive wheels are fixed to the axle shafts which are connected to the differential side gears of the gear set. One rotary encoder is connected to the ring gear in order to measure the rotation angle and angular velocity of the motor. Therefore we apply this mechanical actuation structure for our proposed mobile robotic cart development.

III. CONTROL SYSTEM DESIGN

A. *Inverted Pendulum Control design*

As we described in the previous section, our proposed mobile robotic cart applies Inverted pendulum control in the basic part of its control system to realize the user following behavior. Thus, at first, we describe Inverted pendulum control design of the robotic cart.

Fig.5 shows dynamical model of the robotic cart as the wheeled inverted pendulum. Defining the state parameter vector **X** as

$$\mathbf{X} = \left[x,\ \dot{x},\ \theta,\ \dot{\theta} \right]^T ,$$

then linearizing the dynamical system about

$$\left[x,\ \dot{x},\ \theta,\ \dot{\theta} \right]^T = [0,0,0,0]^T$$

yields the state equation as below,

$$\begin{cases} \dot{\boldsymbol{X}} = \boldsymbol{A}\boldsymbol{X} + \boldsymbol{B}u \\ y = \boldsymbol{C}^T \boldsymbol{X} \end{cases} , \qquad (1)$$

$$\boldsymbol{A} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & a_{23} & a_{24} \\ 0 & 0 & 0 & 1 \\ 0 & 0 & a_{43} & a_{44} \end{pmatrix},\ \boldsymbol{B} = \begin{pmatrix} 0 \\ b_2 \\ 0 \\ b_4 \end{pmatrix},\ C = \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix},$$

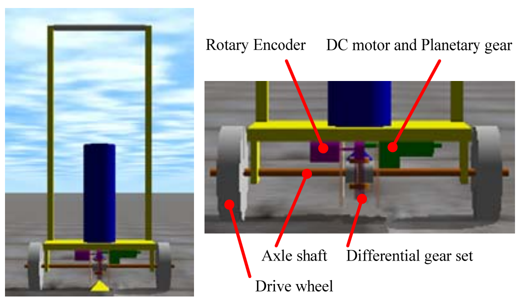


Fig.4 Overview of our proposed mobile robotic cart and its mechanical actuation structure. This structure allows the mobile robotic cart to drive actively and to turn passively, so it keeps the usability of the robotic cart.

where

$$a_{23}=\frac{m^2gl^2}{m^2l^2-(ml^2+I_G)\left(m+M+\frac{J_G}{r^2}\right)},\ a_{24}=\frac{-md\,l}{m^2l^2-(ml^2+I_G)\left(m+M+\frac{J_G}{r^2}\right)},$$

$$a_{43}=\frac{-mgl\left(m+M+\frac{J_G}{r^2}\right)}{m^2l^2-(ml^2+I_G)\left(m+M+\frac{J_G}{r^2}\right)},\ a_{44}=\frac{d\left(m+M+\frac{J_G}{r^2}\right)}{m^2l^2-(ml^2+I_G)\left(m+M+\frac{J_G}{r^2}\right)},$$

$$b_{21}=\frac{-ml^2-I_G}{m^2l^2-(ml^2+I_G)\left(m+M+\frac{J_G}{r^2}\right)},\ b_{41}=\frac{ml}{m^2l^2-(ml^2+I_G)\left(m+M+\frac{J_G}{r^2}\right)}.$$

Then we give the control input u by the state feedback control law to stabilize the dynamical system shown in Eq. (1) as

$$u=-\boldsymbol{k}\boldsymbol{X},$$

then design the appropriate feedback gain k = [k1, k2, k3, k4].

B. Force control to improve the usability performance

We, in addition, apply Force control technology to improve the operational usability in addition to Inverted pendulum control system.

Fig. 6 shows block diagram of our proposed whole control system of the mobile robotic cart. The control module enclosed by the red dashed line is basic inclination angle control system via Inverted pendulum control. The attached Force control part is figured by blue lines as the output feedback control.

When users operate the robotic cart, feedback control gain element for the position control k1 is set to zero to cut off its position feedback control in order to move (or to release from the position control). We, then, set the matrix CT = [0, 1, 0, 0] to derive the velocity of the mobile robotic cart as the output signal for output feedback control. The robotic cart moves according to the force signal added to the handle part, thus we set the parameter D as mechanical impedance which converts the force to the velocity of the robotic cart as shown in Fig.6. This procedure realizes the moving velocity control of the robotic cart.

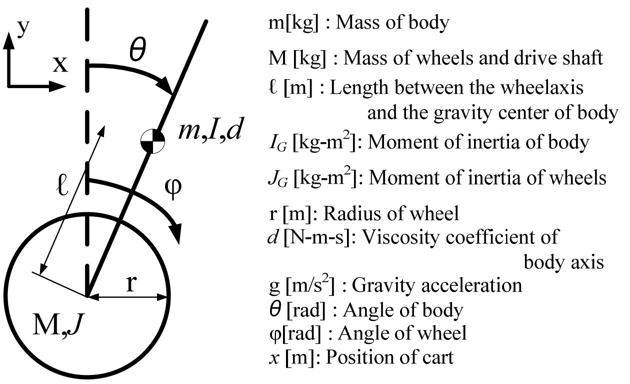


Fig.5 Dynamical system model of the mobile robotic cart which is the wheeled inverted pendulum..

IV. Evaluation by Dynamical Simulation

A. Simulationmodel and its environment

We evaluate the performance of our proposed control system by dynamical computer simulation via Open Dynamics Engine (ODE) [5]. Fig.4 shows the dynamical simulation model which is configurated in ODE environment.

The mechanical actuation system of this simulation model is configurated by one DC motor, one planetary reduction gear, one differential gear set and two drive wheels. The body of the robotic cart is made by rigid metal frame which is assumed as aluminum. One inclination sensor for Inverted pendulum control is fixed by the program applying ODE function. One rotary encoder, as the wheel angle sensor, is attached to the ring gear of the differential gear set in order to measure the position and moving velocity as shown in Fig.4.

The actual physical parameters for the simulation model are shown in Table 1. These parameters are the results of the system identification of the prototype mobile robotic cart machine which is fabricated before [4]. We apply these physical parameters in order to evaluate our proposed control system in the dynamical simulation via ODE environment.

B. Stability evaluation

Our proposed mobile robotic cart applies the differential gear set to actuate the cart itself by one DC-motor and to realize passive turning. The actuation mechanism makes the dynamical system of the mobile robotic cart non-holonomic, so the users cannot control the position of the robotic cart definitely.

In addition, running torque around the Y axis shown in Fig.5 becomes to arise easily, so the torque seems to cause falling down during the robotic cart control via Inverted pendulum control. It becomes a serious problem for the operation of the robotic cart.

TABLE I
PARAMETERS OF THE DYNAMICAL SIMULATION MODEL

Symbol	Unit	Value
m	kg	3.40
M	kg	2.25
l	m	0.1
I_G	$kg\text{-}m^2$	0.052
J_G	$kg\text{-}m^2$	0.086
r	m	0.0725
d	N-m/ (rad/s)	0.011
g	m/s^2	9.8

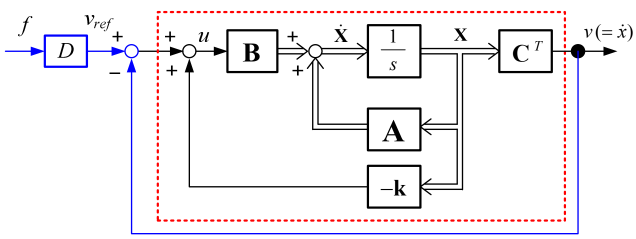


Fig.6 Control system block diagram; Inverted pendulum control module is enclosed by the red dashed line, and the output feedback control system which means Force control system shows the blue lined part.

For the reasons, we evaluated the performance of Inverted pendulum control of the mobile robotic cart by dynamical simulation via ODE, and Fig 7 shows the simulation result. We designed the feedback gain k by applying linear quadratic optimal control. The calculated result became k = [-100, -192.9, -2085.8, -338.8]. Inverted pendulum control embedded in the mobile robotic cart kept its attitude even though its pitching angle and position were left in the state that had been rotated by adding the twist torque. This result shows that Inverted pendulum control system is effective enough to keep the attitude of the robotic cart stably.

C. *Motion control evaluation*

Here we evaluate motion control performance applying the control system shown in Fig.6 by dynamical simulation. The simulation was performed in the following steps in view of the procedure when the user actually use;

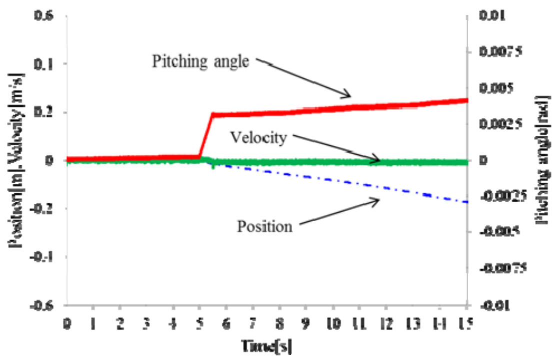
1) Invert pendulum control mode: When the user turns on the power switch, the robotic cart starts up its motion control to keep its attitude and position as general Inverted pendulum control.

2) Force control mode: When the user holds the handle and starts to move, pushing force from the user is added to the handle part. The control system detects the force signal and changes from Inverted pendulum control mode to Force control mode. As described above, feedback gain k changes to

k = [0, -192.9, -2085.8, -338.8],

and the output feedback control system becomes active.

3) Invert pendulum control mode: When the user stops to move, the pushing force added to the handle part become almost zero. The control system detects the signal and returns to the Inverted pendulum control mode.



Adding twist torque: 0.5s

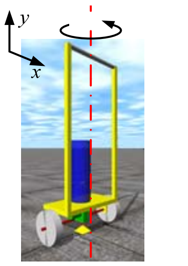


Fig.7 Inverted pendulum control evaluation; After adding the twist torque at 0.5s for the Y axis, behaviors of the robotic cart are observed.
The yawing angle turned for Y axis arises and the cart moved a little. The robotic cart has non-holonomic property, so its position and yawing angle are left in the state that has been rotated. However the stability and inclination angle have been kept as shown in the diagram

The simulation result is shown in Fig.8. At the five seconds after the power was turned on, the pushing force of 3N was added to the handle part. Then the robotic cart started to move from start positon, and it moved to the point of the distance of 1.1 m by keeping its attitude almost zero degree from five to ten seconds. At the time of ten seconds, the pushing force became zero and the robotic cart stopped.

This result shows the motion of the robotic cart switches stably and its attitude is kept almost zero degree. This simulation result indicates that our proposed control system has a high feasibility.

V. PROTOTYPE DEVELOPMENT

A. *Overview of our proposed mobile robotic cart prototype*

We described the feasibility and effectiveness of our proposed mobile robotic cart by several dynamical computer simulations via ODE. Therefore we start to try to develop the mobile robotic cart for the practical use.

Fig.9 shows the overviews of the robotic cart. According to the questionnaire result [2], it is preferred that size of the robotic cart is equivalent to the conventional oxygen equipment carrier or smaller than it. Of course it is also preferred that weight of the robotic cart is equivalent to the conventional carrier or lighter than it. In order to realize ‘small size’ and ‘lightweight’ mobile robotic cart which we propose, we apply small and compact DC blushless motor (EC-i40 /50W with reduction gear and incremental rotary encoder, maxon motor), and differential gear (87466 Complete Differential Gear Set, HPI Racing). These parts are assembled as shown in Fig.9 (b), so the length of right and left axle shaft are different. This mechanical configuration becomes asymmetric, however, the asymmetric mechanism causes no practical problem because the robotic cart is turned passively by the users.

B. *Handle design to improve the usability performance*

Our proposed robotic cart is controlled by pushing force which is added to handle part by the users. This control procedure enables the mobile robotic cart to move by keeping its attitude to the equilibrium point.

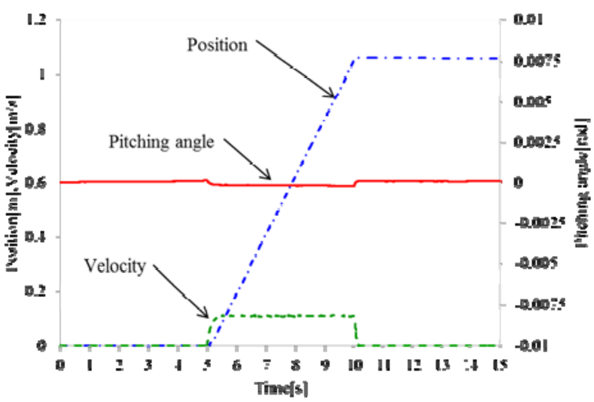
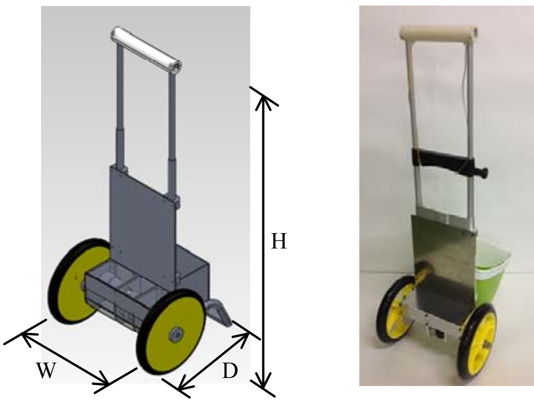


Fig.8 Simulation result of the practical control motion of the robotic cart. The attitude of the cart is always keeping almost zero degree during the motion, and the behaviors of the pitching angle and velocity are very stable even though the control mode is changed.

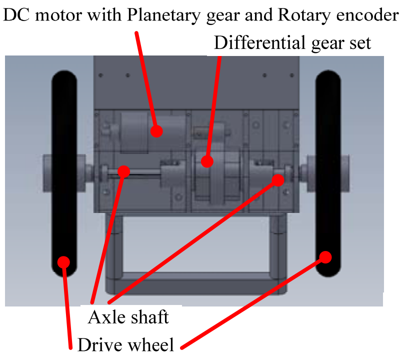
By the way, when the user turns with the robotic cart, the velocity of the user and robotic cart becomes different. Considering the case of the user's motion with the robotic cart, holding the handle of the robotic cart by the user's right hand as shown in Fig.10, the rotation radius of the user's trajectory becomes smaller than the radius of the robotic cart trajectory during left turning, so the cart has to move at a higher velocity than the user. The rotation radius of the user's trajectory also becomes larger than the radius of the robotic cart trajectory during left turning, so the cart has to move at a lower velocity than the user. Because of the need to change the sensitivity of the input signal when the robotic cart turns, as described above, the handle interface of the robotic cart has to detect not only the power of the pushing force but also the turning direction.

In this study we fix two pressure sensors (FSR408, Interlink Electronics Inc.) in the handle part as shown in Fig.11. When the user moves straight, the force added to the handle part pushes two pressure sensors evenly. On the other hand, the force added to the handle part generates different input pressures to the pressure sensors when the user turns, and the sensors detect the difference of the input pressures. Thus it becomes possible to control the sensitivity of the input force at the user and robotic cart turning.

The control reference force signal " f " which is shown in Fig.6 is calculated by the signals from right and left sensors via the equation



(a) Overview of the prototype robotic cart; Width is 328 mm, Depth is 330mm, Height is from 800 to 1000mm adjustable.



(b) Actuation mechanism applied by differential gear set mechanism. In order to reduce the size of cart width, the length of right and left axle shaft are different.

Fig.9 Overview of our proposed robotic cart prototype. The size is decided by users' wish extracted from the questionnaire result from the HOT patients.

$$f = K_S\left(f_R + f_L\right) - K_T\left(f_R - f_L\right) , \quad (2)$$

where f_R and f_L are force signal from the right and left sensors. The parameter K_S is set to adjust sensitivity for forward motion and K_T is also set to adjust sensitivity for turning. In addition, when the user holds the handle of the robotic cart with the left hand, we replace the sign of parameter K_T to change the polar characteristics. Thus our proposed robotic cart is able to be realized with a high operational usability by applying the handle interface which we developed.

C. Evaluation experiments

We carried out several experiments to evaluate the prototype robotic cart. Fig.12 shows the frozen-in-motion pictures of Inverted pendulum control experiment, and Fig.13 shows the result of the experiment.

By applying Inverted pendulum control, the robotic cart, as shown in Fig.13, kept its posture angle to the equilibrium point even though it was in a vibrating manner. On the other hand, when the robotic cart attempted to keep its posture angle, its position drifted by slow degrees as shown in Fig.12 because the robotic cart does not have capability of control around Y-axis rotation. However the robotic cart will be held by the user and its moving direction is also decided by the user's handling. Thus the drifting behavior of the robotic cart will not become a problem.

We, then, carried out the towing experiment. Fig.14 shows the towing experiment, and Table 2 shows the holding force that is measured by the spring scale during the experiment. This result shows that the robotic cart certainly support the user.

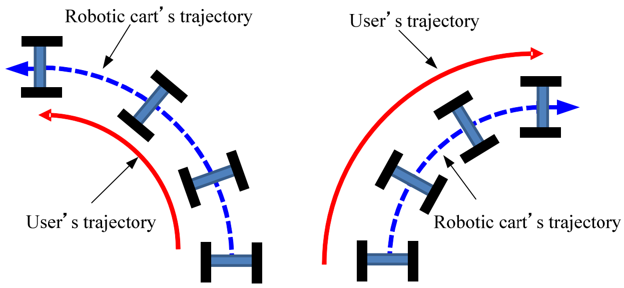


Fig.10 Difference between the user and the mobile robotic cart; the rotation radius of the user's trajectory becomes smaller than the radius of the robotic cart trajectory during left turning, so the cart has to move at a higher velocity than the user.

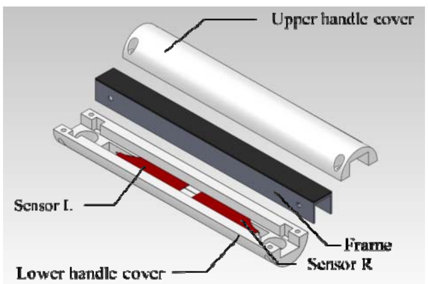


Fig.11 Configuratoin of the handle; there are two pressure sensors which are able to detect the difference between right and left force signal when the user turns with twisting the handle.

VI. CONCLUSION

In this paper, we propose new type of mobile robotic cart which carries the oxygen equipment to support HOT patients' going out. The control system applies force control system attached to Inverted pendulum control system. We also propose an unique actuation mechanism which applies differential gear set.

Then we evaluate the performance of our proposed robotic cart control system by several dynamical simulations. The simulation model of the robotic cart moved stably according to the user's pushing force and never fell down.

Last, we describe the design of new prototype mobile robotic cart in detail and showed the effectiveness of the robotic cart by several experiments.

Then we will evaluate the prototype robotic cart by HOT patients as our future work.

(a) starting position

(b) 5 seconds later

(c) 30 seconds later

(d) 90 seconds later

Fig.12 Inverted pendulum experiment: the prototype robotic cart attempted to keep its posture angle, but it position drifted by slow degrees.

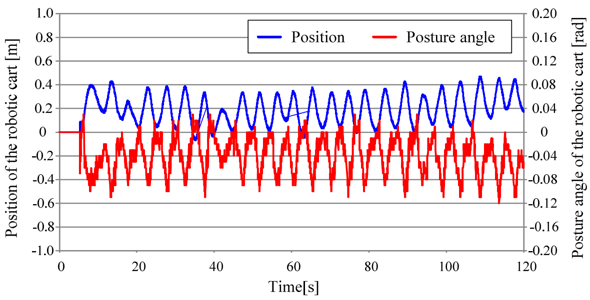


Fig.13 Inverted pendulum experiment: the robotic cart attempt to keep its posture angle to the equilibrium point even though it was in a vibrating manner.

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Table 2 Result of the towing experiment

Symbol	Load [kgf]
Non control	800 - 1200
Force control	800 - 1200
Inverted pendulum and Force control	300 - 500

Fig.14 Towing experiment: the participant towed the prototype robotic cart by applying the spring scale to measure the holding force.