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Author	Masatsugu Iribe, Ryoichi Dasai, Gen Endo, Toshio Takubo, Tetsuya Kinugasa, Koichi Osuka
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Study on a Practical Robotic Follower to Support Home Oxygen Therapy Patients

- Prototype Cart Development Applying the Inverted Pendulum Control -

Masatsugu Iribe, Ryoichi Dasai, Gen Endo, Toshio Takubo, Tetsuya Kinugasa, and Koichi Osuka

***Abstract*— We have proposed a practical power assist robotic cart, which we call 'Robotic Follower', to support daily lives of the patients undergoing Home Oxygen Therapy (HOT). And to achieve the purpose, we have developed several types of Robotic Follower. In this paper, we describe our newly developed Robotic Follower with which the inverted pendulum control technology is applied to control Robotic Follower, and then we investigate its effectiveness and prove its availability.**

I. Introduction

Home Oxygen Therapy (HOT) provides patients with deteriorated pulmonary function primarily resulting from Chronic Obstructive Pulmonary Disease (COPD) with high nasal oxygen levels through a cannula (tube) to supply needed oxygen. HOT enables these patients to treat themselves without being hospitalized while maintaining their quality of life thanks to an oxygen condenser at home or an oxygen tank when they go out. It is reported that over 150,000 subjects are currently undergoing the HOT in Japan, where services for equipment rental/maintenance and insurance services are well set up [1].

In COPD treatment, moderate exercise effectively preserves physical strength, so walking and similar exercise are highly recommended. Fig.1 shows a portable oxygen supply with an oxygen tank and cart generally used by subjects going out. With currently available oxygen tanks, the combined tank and cart mass is about 4.0 to 5.0 kg.

Carrying such a tank up or down slopes, for example, physically burdens pulmonary function and psychological burdens users at the thought of "always" needing an oxygen tank. Such burdens tend to cause subjects to stay home, withdrawing from society. With the objective of helping HOT subjects get out, we have developed mobile robots, which we call **'Robotic Follower'**, carrying oxygen tanks to follow users outdoors [2][3][4]. Specifically, we assume "shopping at a convenience store" because subjects go out most often to shop or to see doctors. With most HOT subjects being aged pensioners, we have tried to make functions as economically burden-free as possible.

Robotic follower use [6] is nothing new and has been substantively tested in hotel lobbies and airports for carrying passenger luggage. Previous research reports robots following or leading users and carrying their luggage [7][8][9].

However, it is difficult to be referred that those research results are equal to practical use enough. To maintain a constant distance from users, such mobile robots have used noncontact and nonintrusive sensors such as image recognition, ultrasonic sensors, beacons, and laser range finders. Actual practical environments may, however, include obstacles and people obstructing robots and users, and causing single or noncontact sensors to fail. This has led to combining a variety of sensors to overcome such difficulties. Ant then, with sensors generally expensive, using more than one may increase overall system cost, making affordable systems difficult to realize and make generally acceptable. Combining sensors may not produce the precision outdoor applications require. Most previous research has confined testing to level ground indoors, limiting their outdoor applications.

In this paper, we therefore propose a new type of Robotic Follower applying Inverted pendulum control technology for realizing affordable ways to follow the users walking. Connecting users and the robot by **"direct handling"** like commonly used suitcases and operating the robot's velocity by its attitude angle via Inverted pendulum control which enables to control the robot's behaviors without complicated sensor fusion described above, of course, with low cost.

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Fig.1 HOT patient's daily life with the oxygen tank and cart

M. Iribe and R. Dasai are with the Dev. of Mechanical and Control Engineering, Graduate school of Osaka Electro- Communication University, 18-8 Hatsu-cho, Neyagawa, Osaka 572-8530, Japan (corresponding author to provide phone: +81-72-824-1131(ext.23.6); fax: +81-72-824-0014; e-mail: iribe@isc.osakac.ac.jp). Then R. Dasai moved to Hitachi Zosen Corp.

G. Endo is with the Dept. of Mechanical and Aerospace Engineering, Graduate school of Science and Engineering, Tokyo Institute of Technology, 2-12-1-I1-60 Ookayama, Meguro-ku, Tokyo, 152-8552, Japan (e-mail: gendo@mes.titech.ac.jp).

T. Takubo is with the First Department of Medicine, Tokyo Women's Medical University, 8-1 Kawada-cho, Shinjuku-ku, Tokyo 162-8666, Japan, (e-mail: ttakubo@chi.twmu.ac.jp).

T. Kinugasa is with the Dept. of Mechanical Engineering, Okayama University of Science, 1-1 Ridai-cho, Kitaku, Okayama, 700-0005, Japan (e-mail: kinugasa@mech.ous.ac.jp).

K. Osuka is with the Dept. of Mechanical Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan (e-mail: osuka@mech. eng.osaka-u.ac.jp)

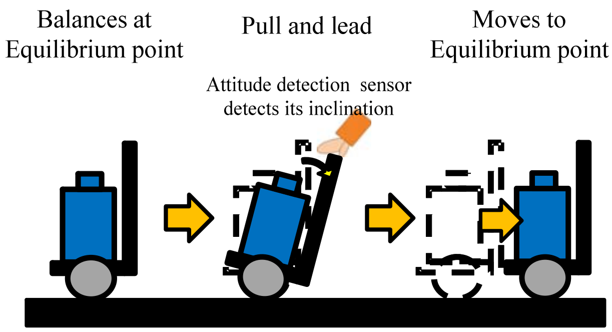


Fig.2 Power assisting principle of the Robotic Follower

Here we describe the principle of the Robotic Follower's control. When the user holds and pulls the handle of Robotic Follower, it leans to the user side and moves forward to reach the equilibrium position to keep its attitude by means of Inverted pendulum control technology to it as shown in Fig.2.

Addition to straight going characteristics described above, turning characteristics of the Robotic Follower is also important. Major past researches on the Inverted pendulum control needed two driving wheels for its locomotion, however, here we propose the concept of it, with low cost and without complicated sensor fusion. So we try to realize "passive turning" by applying a differential gear module for its actuation in order to achieve our concept.

By using the Inverted pendulum control technology and the differential gear's property, we try to develop the Robotic Follower and also try to reduce the burden of carrying loads.

II. The Developed Power Assist Cart

Fig.3 shows our developed Robotic Follower prototype. Its size is 500x170x860 [W x D x H, mm], and mass is 6.1[kg] without the oxygen tank.

The frames of the Robotic Follower are composed of alminum stick type components. Electrical circuit boards are attached to upper side of the Robotic Follower, and an oxygen tank for HOT is mounted on the acrylic plate which is fixed up to upper side of the electrical circuits. Switches to select the cart's control mode and to kill the power supply for emergency stop are attached at both ends of the handle part.

A DC-motor and differential gear unit is applied for actuation, and a rotary encoder is attached to the gear unit to measure the wheels' rotation angle. The motor is with a reduction gear unit (reduction ratio: 1/15, power output is 60W, manufactured by Nakatsu Eng. Co., ltd.) and the differential gear is fixed to transmit the motor's torque to the drive shafts as shown in Fig.4. The differential gear absorbs the difference of wheels' rotation angle, so it enables users to turn the Robotic Follower passively and smoothly. It therefore becomes to enable the Robotic Follower's power assist operation, smooth user-following and passive-turning, by single motor.

For the attitude angle measurement during the Inverted Pendulum Control, we apply one gyroscope sensor (IXZ500, double axis gyro module, manufactured by SparkFun Electronics) and one acceleration sensor unit (KXM52-1050, the unit is assembled by Akizuki Denshi Tsusho Co., Ltd., the sensor device is manufactured by Kionix Inc.). Especially the values from the acceleration sensor are also used to correct the integral error of the gyroscopic sensor.

For the Robotic Follower's velocity and moving distance measurement during the control, we apply one rotary encoder (incremental type, OIS38-TS5300N510-C3-12V, manufac -tured by TAMAGAWA SEIKI Co., ltd.)

These sensor signals described above are input to the control system which is programmed in PC. The signals are amplified by differential amplify circuit to keep the dynamic range maximum. Fig.5 shows the construction of the control system.

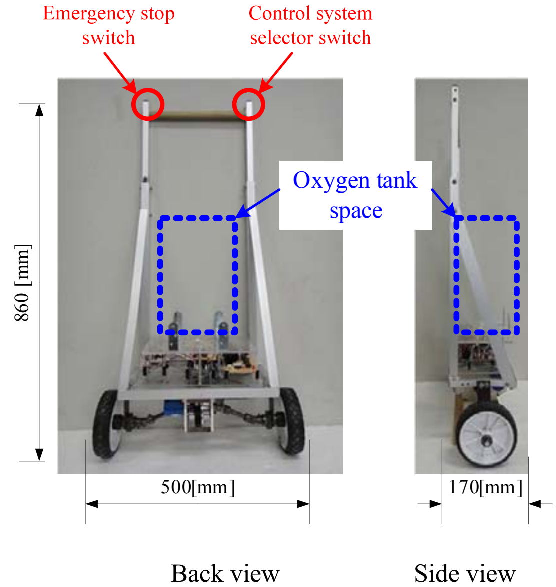


Fig.3 The developed Robotic Follower

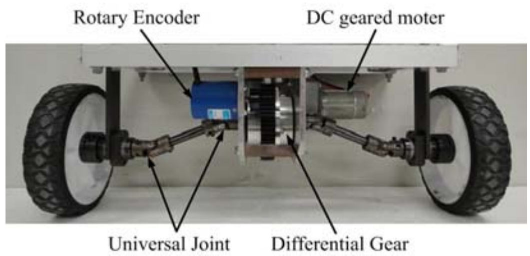


Fig.4 Actuation unit of the Robotic Follower

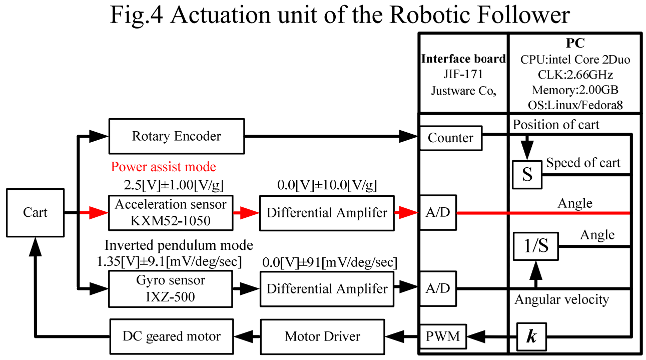


Fig.5 Control system's construction of the Robotic Follower; black lines shows block diagram of the Inverted pendulum control, and the red lines also shows the block diagram of the power assist mode control.

III. CONTROL SYSTEM DESIGN

A. Attitude and position control system design

As described above, our developed Robotic Follower's attitude and user following control are realized by applying the behavior of Inverted pendulum control. So, at first, we design its attitude control system.

Fig.6 shows dynamical model of the Robotic Follower as the wheel type inverted pendulum, and Table 1 also shows dynamical parameters of the system. Defining the state parameters' vector **X** as

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

then linearizing the dynamical system about $[\ x,\ \dot{x},\ \theta,\ \dot{\theta}]$ = [0, 0, 0, 0] yields the state equation as below,

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

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

Here, parameter x [m] and $\dot{x}$ [m/s] shows the position and velocity of the cart, and θ [rad] and $\dot{\theta}$ [rad/s] shows the angle and angular velocity of the pendulum part.

For stabilizing the dynamical system shown in Eq.(1), we give the control input u by the state feedback control law as

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

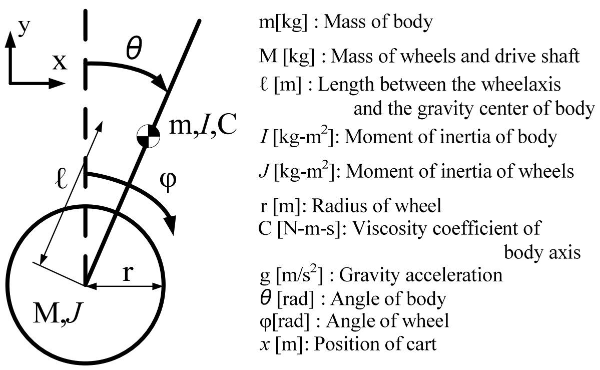


Fig.6 System model of the cart

Table 1 Parameters of the system

m	[kg]	3.85
M	[kg]	2.25
ℓ	[m]	0.1
I	[kg-m^2]	0.0878
J	[kg-m^2]	0.849×10^{-3}
r	[m]	0.0725
C	[N-m-s]	0.0586
g	[m/s^2]	9.8

and then design the appropriate feedback gain **k**. The feedback gain **k** is calculated by using Matlab's "lqr" function. Vector (2) shows the calculated results.

$$\boldsymbol{k} = \left[-100.00, -155.23, -710.65, -159.33\right] \qquad (2)$$

B. Disturbance sensitivity analysis

Our developed Robotic Follower applies the differential gear to actuate the cart itself by one DC-motor and to realize passive turning. And as applying the actuation system, we face two problems.

Firstly, applying the actuation system makes the cart's dynamical system nonholonomic, so we are not able to control the cart's position. Although, in actual use, users hold and pull the cart directly, so it would not matter.

Secondly, as applying the actuation system, running torque around the Y axis in Fig.6 arises easily. The torque seems to cause falling down during the cart's attitude and position control via Inverted pendulum control. It becomes a serious problem for the cart's operation.

However, the torque can be explained as a kind of torque disturbance to the DC-motor's output axis. So we can evaluate magnitude of the torque disturbance's effect by calculating Bode gain of sensitivity functions from torque to outputs.

Fig.8 shows calculated results of Bode gain of the sensitivity function from the torque to position and angle outputs. From these results, we can confirm that the maximum value of Bode gain of sensitivity function from the torque to position output becomes -40[dB] and the maximum value from the torque to angle output becomes -55[dB]. It is therefore believed that the torque disturbance has little effect on the stability of control system, so applying the differential would not matter, too.

C. Moving and following control system design

The attitude and position control system via Inverted pendulum control described above needs the reference position for its control. However, in actual use, users don't set out their reference position or trajectories. We therefore try to realize the control system which is able to control the cart's moving and following the users without reference position or trajectories.

For this purpose, we design another control system for the cart's moving and following user control. We realized the control system by cutting off the position and velocity feedback by setting their feedback gains zero as shown in Fig.9. As designing the control system, the cart becomes to move to its inclined direction.

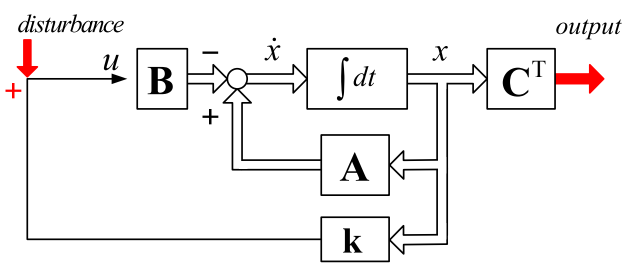
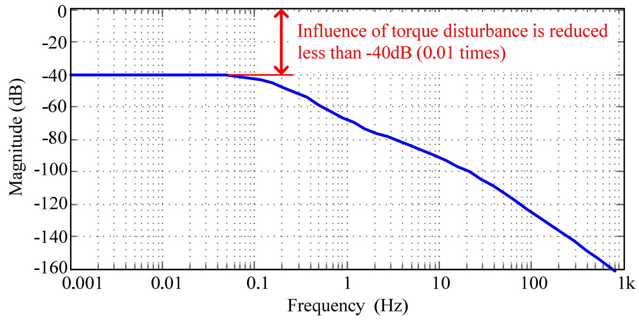
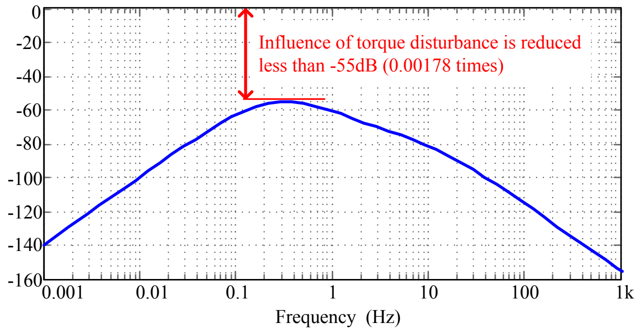


Fig.7 Sensitivity function from disturbance to output



(a) Transfer function between disturbance and angle



(b) Transfer function between disturbance and output position

Fig.8 Bode diagram of the sensitivity functions

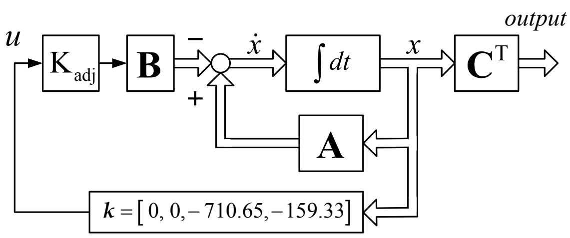


Fig.9 Block diagram of moving and following control system

In addition, we insert a proportional gain K_{adj} as shown in Fig.9 for adjusting the sensitivity between the cart's inclined angle and moving velocity.

Then we confirm the stability of this control system by calculating its eigenvalues. Fig.10 shows the calculated results; eigenvalues of the cart's stop and hold control system, eigenvalues of the cart's moving and following control systems.

As shown in Fig.10, real parts of eigenvalues of the cart's stop and hold control system are all negative, so the system is stable. Eigenvalues of the cart's moving and following control system are shown in Fig.10, in the case of K_{adj} = 0.1, 0.3, 0.5, 1.0.

In the cart's moving and following control system, eigenvalues of the position mode and velocity mode are zero, so the system shows in stability-limit for the position and velocity control. However, in the attitude angle mode and angular velocity mode, real parts of these modes' eigenvalues are negative. Therefore the control systems, in the case of K_{adj} = 0.1, 0.3, 0.5, 1.0, are all stable in varying degrees.

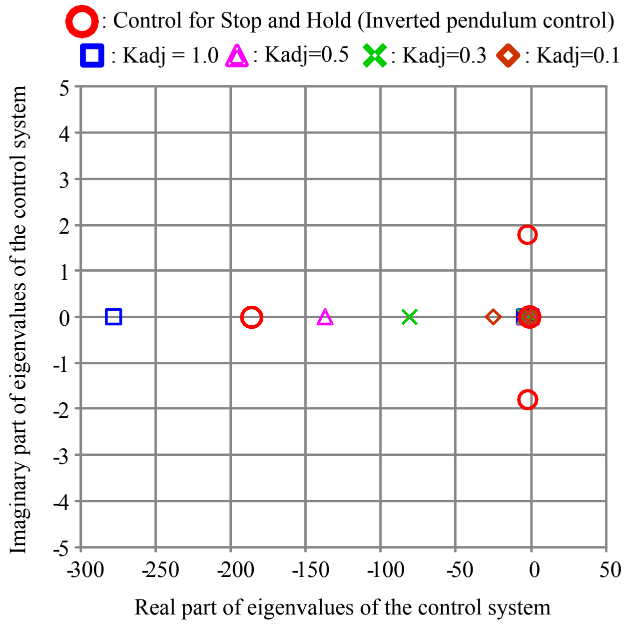


Fig.10 Stability analysis of the control system

In actual use, when the cart needs to stop and hold its attitude and position, the control system described in section 3.A is selected. And when the cart needs to move, the above mentioned control system is selected. The control system selection is switched by operating the button switch on the cart's handle part.

IV. Experiments and Evaluation

A. Attitude control experiment

Fig. 11 shows the experimental result of developed cart's attitude and position control. The experiment started from stationary state at the equilibrium point, the reference point $\mathbf{X}_{ref} = [0, 0, 0, 0]^T$ is given, and the sampling time is 1ms. As shown in Fig.11, the cart is able to keep its attitude and position.

At the moment of 10 [s] and 20 [s], the experimenter pushes the cart consciously by his hand, so it moves and leans significantly. However, adding such the disturbances, the cart keeps its attitude and position around the equilibrium point.

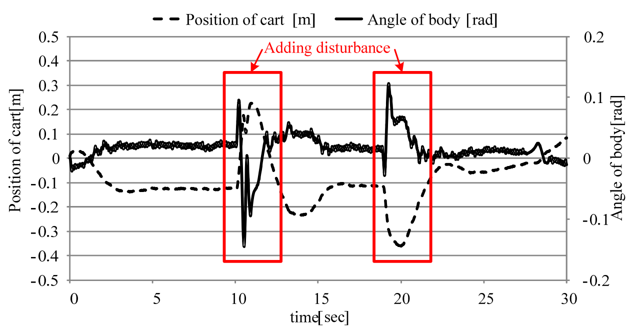


Fig.11 Experimental result of the attitude and position control

B. *Power assist operation via switching control law*

Applying a procedure of switching control law described in section III-C, we experiment the power assist operation of the developed cart. Fig.12 shows time-series changes of the attitude angle and position, and Fig.13 shows the photographic playback of experiment in operation. For this experiment, we set up the proportional gain Kadj as 0.1 because the attitude angle control is very sensitive.

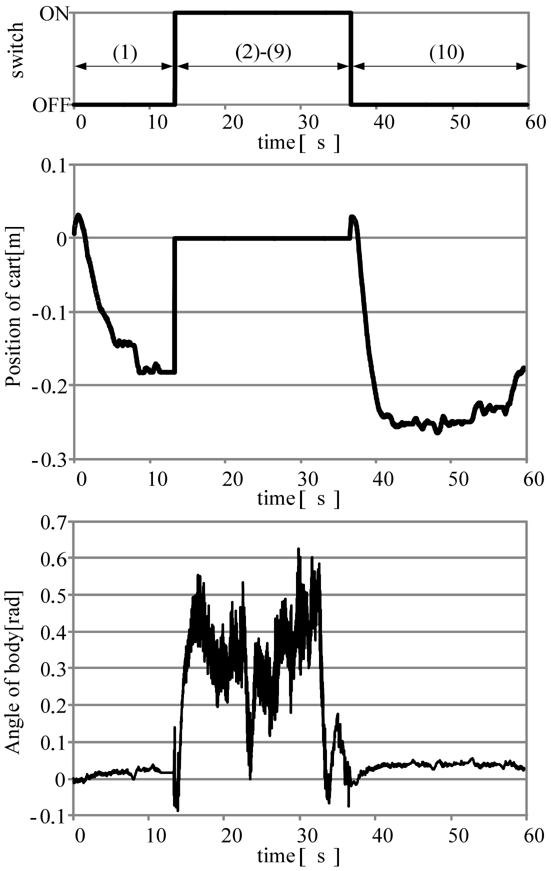


Fig.12 Experimental results of the power assist operation

In the case of Fig.13-1, the cart's control system is set to the attitude and position control via Inverted pendulum control, and the cart keep its attitude angle and position around the equilibrium point $[x, \dot{x}, \theta, \dot{\theta}] = [0, 0, 0, 0]$.

Then, in the case of Fig.13-2, the experimenter turns on the control system select switch on the handle of the cart to change to the moving and following control system.

From Fig.13-3 to Fig.13-5, it is confirmed that the experimenter pulls the cart and it is able to follow the experimenter stably. Value of the rotary encoder is reset and held to zero during this control, so values of the position show 0.0 [m]. And then, the figures from Fig.13-6 to Fig.13-9 show a passive turning process. This result clarifies the effectiveness of differential gear for turning passively.

In the case of Fig.13-10, the experimenter turns off the control system select switch again to replace the control system. After moving and following operation, as shown in the figure, the cart is able to keep its attitude and position.

As mentioned above, it is thought that the power assist cart which applies the principle of Inverted pendulum control technology can be realized..

C. *Evaluation test result*

Here we compare our developed power assist cart to a commonly used cart to verify the effectiveness of power assist.

Circumstance of the evaluation test is shown in Fig.14. The cart is connected to the spring balance scale, and another side of the scale is also connected to the slide ring which is let through to a plastic pole. The plastic pole is spanned over 1.0 [m] height. And the cart moves along with the plastic pole slowly by constant velocity to avoid generating the acceleration. We measure the normal force of the cart by spring balance scale as the cart's pulling load during the cart's moving at constant velocity.

Fig.15 shows results of the evaluation test. As shown in Fig.15 (a), normal force loads of the commonly used cart at stop and move are in proportion to the added load mass. And as shown in Fig.15 (b), normal force load at stop is in proportion to the added load mass, however, normal force at move is constant for all that the added load mass increases.

These results show that our developed cart and its control law are effective for the power assist function evidently.

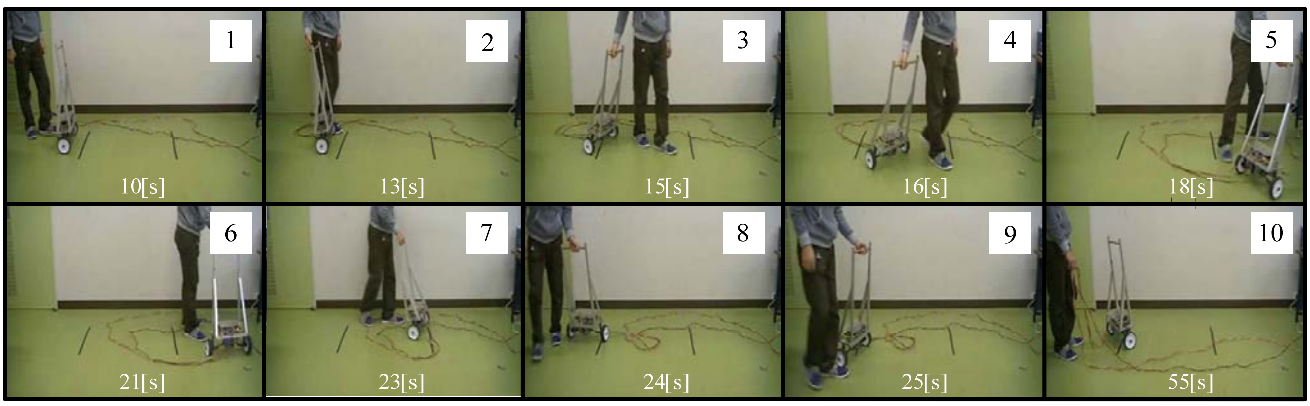


Fig.13 Photographic playback of the power assist operation experiment

V. CONCLUSION

In this paper we propose a new type of power assist type robotic cart for HOT patients' assistance by applying Inverted pendulum control technology with the differential gear module for realizing affordable ways to follow the users walking.

For this purpose, we developed a prototype Robotic Follower and its control method, and then we confirmed the effectiveness of them for users' power assist behavior. And for the future work we will try to experiment with HOT patients by using our prototype Robotic Follower as user's tests shown in Fig. 16.

APPENDIX

Actual parameters of matrix **A** in Eq.(1) are as below;

$$a_{23} = \frac{m^2 g l^2}{m^2 l^2 - (ml^2 + I)\left(m + M + \frac{J}{r^2}\right)}, \quad a_{24} = \frac{-mlC}{m^2 l^2 - (ml^2 + I)\left(m + M + \frac{J}{r^2}\right)},$$

$$a_{43} = \frac{-\left(m + M + \frac{J}{r^2}\right)mgl}{m^2 l^2 - (ml^2 + I)\left(m + M + \frac{J}{r^2}\right)}, \quad a_{44} = \frac{\left(m + M + \frac{J}{r^2}\right)C}{m^2 l^2 - (ml^2 + I)\left(m + M + \frac{J}{r^2}\right)},$$

$$b_2 = \frac{-(ml^2 + I)}{m^2 l^2 - (ml^2 + I)\left(m + M + \frac{J}{r^2}\right)}, \quad b_4 = \frac{ml^2}{m^2 l^2 - (ml^2 + I)\left(m + M + \frac{J}{r^2}\right)}.$$

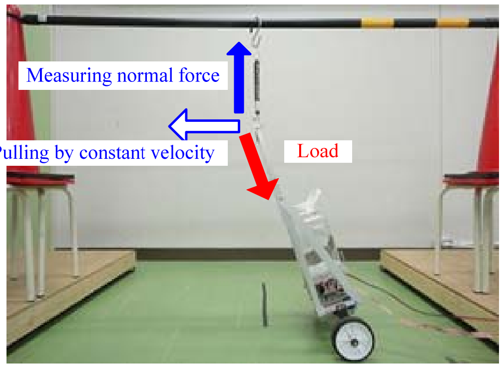
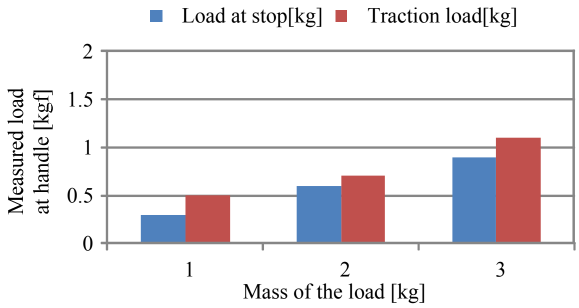
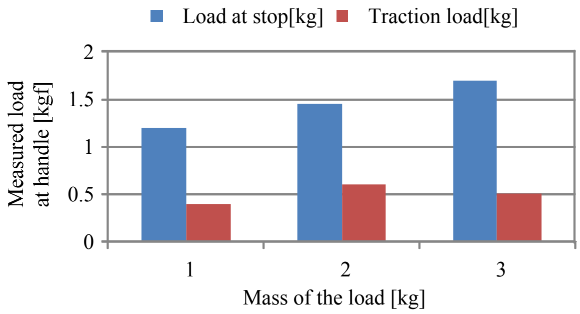


Fig.14 Evaluation test of power assist effectiveness

Fig. 16 Prototype testing by HOT patients



(a) in the case of commonly used cart



(b) in the case of developed cart

Fig.15 Evaluation test result of two carts

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