Posture Stabilization Control Compensating Variation of Body Center of Gravity in Underactuated System

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***Abstract*—With the recent decreasing birthrate and aging population, cooperative robots are attracting attention for a new workforce. As cooperative robot, robots with a small footprint and high center of gravity, like humans, can be considered more suited. Robots with these features are generally unstable, and posture stabilization control becomes important when the center of gravity is shifted due to holding objects or other factors. Therefore, in this study, we select a two-wheeled robot as the target robot and carrying luggage as the target motion, and establish the posture stabilization. Many studies about two-wheeled transport robots do not adequately consider the shift in the center of gravity, which may lead to rapid acceleration and negatively affect position tracking performance. The purpose of this paper is to compensate the shift in the center of gravity of the vehicle, and can perform transport operations in a steady state. To achieve this purpose, we propose to apply Repulsive compliance control(RCC) to a two-wheeled transport robot. Several experiments show its effectiveness.**

***Index Terms*—Two-wheeled robot, Posture Stabilization Control, Repulsive compliance control(RCC)**

I. INTRODUCTION

In recent years, the decreasing birthrate and aging population have become serious problem all over the world, and it leads to the problem of labor shortage. Currently, factories and logistics warehouses require hundreds of workers. In the future, as the workforce becomes even more inadequate, it will be necessary to ensure productivity with less workers. A way to increase productivity per person would be for humans and robots to work together. As many things within a factory or logistics site are made to fit humans, the scaffolds on which they work are narrow and the objects they work on are often at the height of a person. To work with humans in such an environment, robots with a small footprint and high center of gravity, like humans, can be considered more suited. Hence, regardless of legged robot or wheeled robot, more and more robots with small footprints and a high center of gravity are expected to be developed. Obviously, the mechanisms of such robots are generally unstable, and it is necessary to perform various motions while maintaining their balance. In this study, the target motions are set to holding an object. And we selected an inverted two-wheeled robot like Fig. 1 because it has a small footprint and can be simply configured to verify the control system.

A two-wheeled robot is underactuated system with two actuators mounted on the wheels, whereas they have three degrees of freedom: body posture and body position (x and y directions). It is statically unstable, but the vehicle attitude can be stabilized by control. In general, however, when the body center of gravity is shifted by holding an object or being applied impact force or otherwise, the pitch angle of the robot is tilted. As a result, the robot moves forward in the direction of the tilted posture and cannot stop on the spot. Therefore, it is essential to have a control system that can deal with the shift in the center of gravity.

Many studies and developments about two-wheeled robots have been conducted in the mobility field. A typical example is segway[1] as a personal mobility robot. Nakamura et al. developed a wheelchair-type two-wheeled robot. They achieved attitude stabilization by determining control inputs based on Lyapunov's stability theorem [2]. They also introduced a pitch angle disturbance observer (PADO) to compensate for disturbances in the vehicle posture(pitch) angle direction, and a wheel disturbance observer (WDOB) to compensate for disturbances in the wheel drive direction. Synthesized pitch angle disturbance observer (SPADO), which collectively compensates for pitch angle disturbances and wheel disturbances, has also been developed. For the stabilization of a two-wheeled wheelchair robot, Kuramatsu and Acar et al. proposed center of gravity deviation compensation utilizing repulsive compliance control (RCC), which can suppress rapid accel-

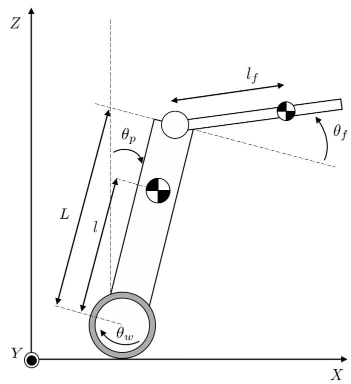


Fig. 1. Side view of a two-wheeled robot with arm system

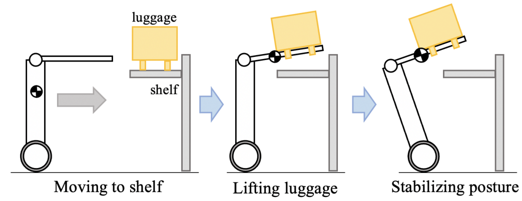


Fig. 2. Image of lifting luggage motion

eration of the vehicle body caused by external disturbances during boarding [3] [4] [5]. While general compliance control achieves motion that follows the reaction force by determining the position command value according to the force response value, RCC achieves motion that opposes the reaction force by generating a command value in the opposite direction to the force response, as the name ”repulsive” indicates. there are other studies using RCC. Hirata et al. set the RCC gain variable in order to achieve step climbing easily and stabilize human posture after step climbing [10]. They used RCC to compensate for only transient center of gravity shift to achieve climbing over steps, and did not check for constant shift. In the study by Kuramatsu et al. it is also not yet confirmed whether the RCC can deal with constant shift, because people balance themselves while driving.

In addition to the mobility field, there have been studies on the application of two-wheeled robots as transport robots. Salerno and Angeles desinged the controller with a dominant second-order pole technique and a linear-quadratic regulator approach in order to achieve robustness against parametric uncertainty and unmodeled dynamics uncertainty, when payload was changed a lot [6]. Gopinath and Jisha proposed a gain scheduled LQR to achieve balancing of two wheeled robot under varying loads [7]. Sayidmarie analyzed the influence of the moving height of payload on the stability of two wheeled robot [8]. However, in [6], [7] and [8], it was assumed that the payload rode just above the vehicle’s center of gravity, and the forward and backward shift in the center of gravity by carrying payload was not considered. Takei et al.[9] constructed two subsystems, a balancing and traveling control subsystem and a navigation subsystem, to realize baggage handling and navigation for a two-wheeled robot. Takei et al. have not built a mechanism to constantly compensate for the shift in the center of gravity of the vehicle body caused by loading luggage, and only compensate occasionally, which could be problematic. In the position tracking experiment, there was a large tracking error between the command value and the actual position. Effects of shift in center of gravity are not properly handled, and it is hard to say that positional control is realized.

Therefore, the purpose of this paper is to construct a control system that can stabilize the vehicle body and accurately control its position even if the center of gravity of the vehicle body is constantly shifted due to carrying luggage or other reasons. To achieve this purpose, we propose to apply RCC to a robot that carries luggage. As mentioned above, there are research applied to two-wheeled personal mobility vehicles, but no research applied to movements of carrying luggage that cause constant shift of center of gravity. It is necessary to confirm experimentally that RCC is effective not only for humans but also for motions that involve holding objects. RCC derive pitch angle command which has opposite direction of reaction torque, hence it can compensate the center of gravity position deviation. It is also advantageous that this method does not require luggage information. For the other control systems, PI controller is used for position control and Lyapunov-based PD controller is used for the pitch angle control, and both are connected in a cascade structure. SPADO is also applied to compensate for integrated disturbances.

The structure of this paper is as follows: In section II, modeling of a two-wheeled robot is described, and in section III, the design of the control system is explained. In section IV, the effectiveness of the proposed method is confirmed by some experiments. Finally, in section V, we summarize the conclusions of this paper.

II. MODELING

In this section, we explain the two-dimensional modeling. In this paper, we considered a motion to carry a luggage, and developed a control system that can deal with the shift of the center of gravity. The robot with the model mechanism shown in Fig. 1 is set to a target robot. Arms driven by a motor are attached to the top of the vehicle body. The arm part goes under the luggage and can lift the load automatically by rotating the arm upward. A simple image is shown in Fig. 2. Some notations are listed in Table I.

A. Kinematics

For the simplicity of the model, we consider a two-dimensional model, although the actual robot also performs turning movements. We made an assumption to derive the kinematics as follow.

- Friction between the wheels and the ground is considered, and wheels do not slip.

From an assumptions, (1) is obtained.

$$\dot{X} = R\dot{\theta_w} \tag{1}$$

TABLE I

NOTATIONS ABOUT THE TWO-WHEELED ROBOT WITH ARM

Notation	Explanation
θ	Angle
R	Radius of wheels
L	Height of body
l	Distance between actuator axle and the center of gravity
$\bigcirc_w$	About wheels
$\bigcirc_p$	About pitch angle
$\bigcirc_f$	About arm
n	Gear ratio

B. Dynamics

Dynamics of the two-wheeled robot with arm system is obtained as (2) by solving the Lagrange's equation.

$$\boldsymbol{M}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \boldsymbol{H}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + \boldsymbol{G}(\boldsymbol{\theta}) = \boldsymbol{E}\tau \tag{2}$$

$$\begin{aligned} \boldsymbol{\theta} &= \begin{bmatrix}\theta_w & \theta_p & \theta_f\end{bmatrix}^T \\ \boldsymbol{E}\tau &= \begin{bmatrix}n\tau_w^{ref} & -n\tau_w^{ref} & n_f\tau_f^{ref}\end{bmatrix}^T \\ \boldsymbol{M}(\boldsymbol{\theta}) &= \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33}\end{bmatrix} \\ \boldsymbol{H}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) &= \begin{bmatrix} h_1 \\ h_2 \\ h_3 \end{bmatrix}, \boldsymbol{G}(\boldsymbol{\theta}) = \begin{bmatrix} 0 \\ g_2 \\ g_3 \end{bmatrix} \end{aligned} \tag{3}$$

$\boldsymbol{M}$ is inertia matrix, $\boldsymbol{H}$ is centrigugal and Coriolis term, $\boldsymbol{G}$ is gravity term. $\tau_w^{ref}, \tau_f^{ref}$ is torque reference of wheel and arm system respectively.

III. CONTROL SYSTEM

In this section, control system is considered. The block diagram of the entire system is shown in Fig. 3. As shown in Fig. 3, the arm system and the body system are controlled independently. In reality, they should interfere with each other, but this simple structure is achieved by building observers in both systems to compensate for the interference components in each. Each control system is described below.

A. PD control and DOB for arm system

By driving arm system, luggage can be automatically picked up from the shelves, like Fig. 2. The Disturbance Observer (DOB)[11] is implemented with PD control in order to robustly design the position control of arm system. DOB estimates all disturbances, including modeling errors and interference terms, from the input torque and output state. Disturbances are compensated by feeding them back. By introducing all disturbance $\tilde{\tau}_f^{dis}$, motion equation of arm is obtained as (4). $\bigcirc_{nii}$ represents nominal value of $\bigcirc_{ii}$.

$$m_{n33}\ddot{\theta}_f + \tilde{\tau}_f^{dis} = n_f\tau_f^{ref} \tag{4}$$

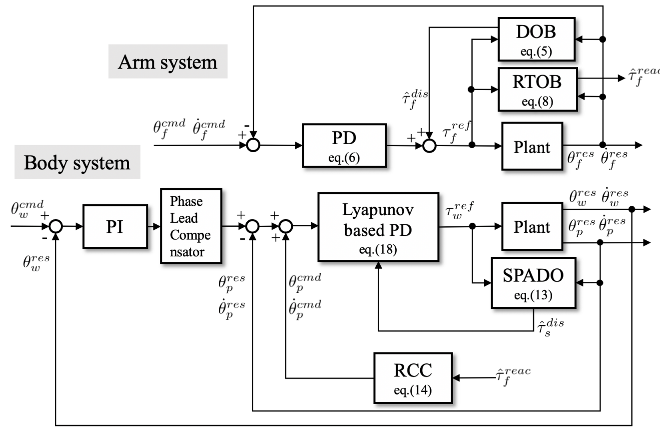


Fig. 3. Block diagram of the entire system

Using pseudo differentiation, the estimated disturbance can be obtained as (5). And torque reference is obtained as (6) from the PD control and the estimated disturbance.

$$\hat{\tau}_f^{dis} = \frac{g_f}{s+g_f}\left\{m_{n33}g_f\dot{\theta}_f^{res} + n_f\tau_f^{ref}\right\} - m_{n33}g_f\dot{\theta}_f^{res} \tag{5}$$

$$\tau_f^{ref} = K_{pf}(\theta_f^{cmd} - \theta_f^{res}) + K_{df}(\dot{\theta}_f^{cmd} - \dot{\theta}_f^{res}) + \hat{\tau}_f^{dis} \tag{6}$$

Here, K_{pf}, K_{df}, g_f are P gain, D gain and cut-off frequency of pseudo differentiator respectively. The above allows arm to achieve robust positional control even with external disturbances and to lift luggage.

B. RTOB of arm system

Reaction Torque Observer (RTOB)[12] estimates only the reaction force torque from the total disturbance torque. In this study, it is conducted to estimate reaction torque of luggage loading, which is used for RCC. Reaction torque can be estimated as (7) and can be transformed as (8) by using pseudo differentiation.

$$\tilde{\tau}_f^{reac} = \tilde{\tau}_f^{dis} - \tau_g - F - D\dot{\theta}_f^{res} \tag{7}$$

$$\begin{aligned}\hat{\tau}_f^{reac} = \frac{g_{fr}}{s+g_{fr}}&\left\{m_{n33}g_{fr}\dot{\theta}_f^{res} + n_f\tau_f^{ref} - \tau_g - F - D\dot{\theta}_f^{res}\right\} \\ &- m_{n33}g_f\dot{\theta}_f^{res}\end{aligned} \tag{8}$$

Here, τ_g, F, D are identified gravity torque of fork part, coulomb friction, and viscous friction respectively. By subtracting those from the total disturbance, the reaction torque is obtained.

C. Synthesized pitch angle disturbance observer (SPADO)

Also in the body system, a disturbance observer called SPADO was implemented to compensate for disturbances and provide robust attitude stabilization. SPADO estimates the whole disturbance, combining the pitch angle disturbance and the wheel disturbance. Block diagram is shown in Fig. 4.

First, the motion equation of wheel and pitch angle are written as equation (9), (10) respectively.

$$m_{n11}\ddot{\theta}_w = n\tau_w^{ref} - \tilde{\tau}_w^{dis} \quad (9)$$

$$m_{n21}\ddot{\theta}_w + m_{n22}\ddot{\theta}_p = -n\tau_w^{ref} - \tilde{\tau}_p^{dis} \quad (10)$$

$\tilde{\tau}_w^{dis}$ and $\tilde{\tau}_p^{dis}$ are disturbances which include interference, modeling error. (10) is transformed as (11) by substituting (9).

$$\frac{n(m_{n21}+m_{n11})}{m_{n11}}\tau_w^{ref} + m_{n22}\ddot{\theta}_p = -\tilde{\tau}_s^{dis} \quad (11)$$

$$\tilde{\tau}_s^{dis} = \tilde{\tau}_p^{dis} - \frac{m_{n21}}{m_{n11}}\tilde{\tau}_w^{dis} \quad (12)$$

where $\tilde{\tau}_s^{dis}$ in (12) is called synthesized pitch angle disturbance, and estimated as equation (13) by using pseudo differentiation.

$$\hat{\tau}_s^{dis} = \frac{g_s}{s+g_s}\left\{m_{n22}g_s\dot{\theta}_p^{res} - \frac{n(m_{n21}+m_{n11})}{m_{n11}}\tau_w^{ref}\right\} - m_{n22}g_s\dot{\theta}_p^{res} \quad (13)$$

By feeding it back, robust robot attitude stabilization is achieved against all disturbances.

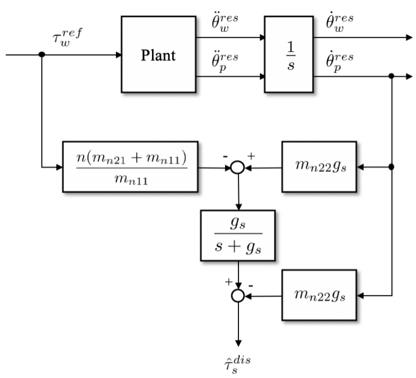


Fig. 4. Block diagram of SPADO

D. Repulsive Compliance Control (RCC)

RCC generates a pitch angle command value that guarantees the center of gravity position deviation when luggage is ridden. RCC is expressed as equation (14) with some gains M_c, D_c, K_c, A_c, where M_c, D_c, K_c, A_c represents virtual inertia, viscosity, elastic modulus, and assist gain, respectively. And $\hat{\tau}_f^{reac}$ is the reaction torque estimated by arm RTOB.

$$M_c\ddot{\theta}_p^{cmd} + D_c\dot{\theta}_p^{cmd} + K_c\theta_p^{cmd} = -A_c\hat{\tau}_f^{reac} \quad (14)$$

From (14), RCC has a similar form to general compliance control, except that the negative sign on the right side generates a command value in the opposite direction of the force response value.

Fig. 5(a) shows luggage loading motion without RCC. In this case, robot cannot compensate for constant shift in vehicle center of gravity caused luggage loading.As a result, robot accelerates rapidly and failures to maintain in place. Fig. 5(b) shows luggage loading motion with RCC. The RCC generates a pitch angle in the opposite direction of the reaction torque due to the luggage, thus it can compensate for constant shift and prevent sudden acceleration. And it can maintain in place.

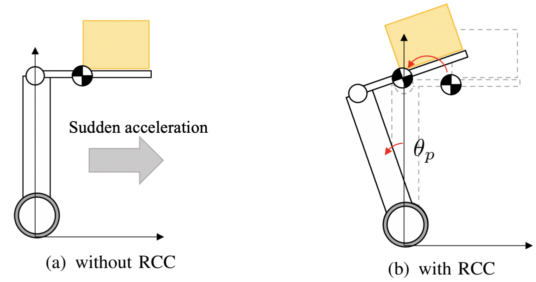


Fig. 5. Overview during loading luggage

E. Lyapunov based PD control

In this section, pitch angle stabilization control based on Lyapunov stability theorem is represented.

First, Lyapunov function V and its derivative are set as in equation (15), (16).

$$V = \frac{1}{2}K_1(\theta_p^{cmd} - \theta_p^{res})^2 + \frac{1}{2}K_2(\dot{\theta}_p^{cmd} - \dot{\theta}_p^{res})^2 \quad (15)$$

$$\dot{V} = (\dot{\theta}_p^{cmd} - \dot{\theta}_p^{res})\Big\{K_1(\theta_p^{cmd} - \theta_p^{res}) + K_2(\ddot{\theta}_p^{cmd} - \ddot{\theta}_p^{res})\Big\} \quad (16)$$

K_1, K_2 are positive gain. Then (16) is transformed as (17), by substituting (11), which is obtained by combining of the motion equations of wheel and pitch angle.

$$\dot{V} = (\dot{\theta}_p^{cmd} - \dot{\theta}_p^{res})\Big\{K_1(\theta_p^{cmd} - \theta_p^{res}) + K_2\Big(\ddot{\theta}_p^{cmd} + \frac{1}{m_{n22}}\Big(\frac{n(m_{n21}+m_{n11})}{m_{n11}}\tau_w^{ref} + \tilde{\tau}_s^{dis}\Big)\Big)\Big\} \quad (17)$$

Here, $\tilde{\tau}_s^{dis}$ represent the whole disturbance and it is estimated by SPADO. If equation derivative of lyapunov function is negative semi-definite, pitch angle can be stabilized. Hence, torque reference is set as equation (18) so that (17) become negative semi-definite.

$$\tau_w^{ref} = -\frac{m_{n11}m_{n22}}{n(m_{n21}+m_{n11})}\Big\{\ddot{\theta}_p^{cmd} + \frac{K_1}{K_2}(\theta_p^{cmd} - \theta_p^{res}) + \frac{K_3}{K_2}(\dot{\theta}_p^{cmd} - \dot{\theta}_p^{res})\Big\} - \frac{m_{n11}}{n(m_{n21}+m_{n11})}\hat{\tau}_s^{dis} \quad (18)$$

Here, $\frac{K_1}{K_2}$ equals K_p(P gain), and $\frac{K_3}{K_2}$ equals K_d(D gain). If $\hat{\tau}_s^{dis}$ equals to the actual value $\tilde{\tau}_s^{dis}$, (17) is converted to (19) using (18), and $\dot{\theta}_p \rightarrow \dot{\theta}_p^{cmd}, \theta_p \rightarrow \theta_p^{cmd}$ are guaranteed.

$$\dot{V} = -K_3(\dot{\theta}_p^{cmd} - \dot{\theta}_p^{res})^2 \leq 0 \quad (19)$$

F. PI control and Phase lead compensator

While the control described so far is intended to stabilize the robot's posture, the transfer robot must also perform the function of moving to the desired position and carrying cargo. Hence, for vehicle position control, PI controller and phase lead compensator are employed. Without phase lead compensation, the pitch angle oscillates in experiment. Therefore, in this paper, phase lead compensation is applied to eliminate the unstable pole that cause the oscillation.

IV. EXPERIMENT

In this section, 2 types experiments are conducted. The parameters used in the experiments are listed in Table II.

- Experiment 1: Lifting luggage manually
- Experiment 2: Position tracking and lifting luggage automatically

A. Experiment 1

Condition: Experiment 1 evaluated the stability when luggage was loaded off the center of gravity of the vehicle body. After stabilizing the vehicle in an inverted position, a 2 kg luggage was manually loaded on the arm, which was controlled to be at right angles to the vehicle body. To verify the effect of RCC only, only pitch angle control, which is inner loop in Fig. 3, was conducted without position feedback, which is the outer loop. In the experiment 1, with and without RCC were compared.

Result: Result of experiment 1 is shown in Fig. 6. Fig. 6(a) and (c) show the transport distance and pitch angle without RCC. The luggage is loaded in blue area. The pitch angle remains the same even with luggage on board, and the vehicle continues to move forward. Without RCC, the vehicle cannot compensate for the shift in the center of gravity due to luggage loading, causing the vehicle to accelerate. Fig. 6(b) and (d) shows the transport distance and pitch angle with RCC. The luggage is loaded in yellow area. After luggage loading, the pitch angle immediately changes to a negative value. The travel distance also converged to a constant value. This result indicates that RCC generates a pitch angle command value opposite to the external force due to luggage loading and can compensate for the constant shift in the center of gravity of the vehicle body.

B. Experiment 2

Condition: Experiment 2 evaluated the accuracy of position tracking and confirmed the realization of automatic loading and unloading luggage operations with RCC. The operation performed in Experiment 2 is shown in Fig. 7. The 14 motions in the figure are as follows.

1-4 The machine moves from the start position to the shelf by moving forward and turning (t=0-35).

5 Arms are driven to automatically load the luggage onto the shelf (t=40).

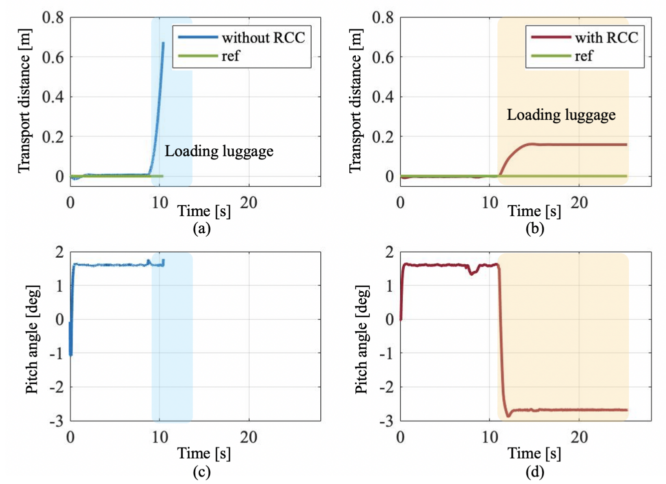


Fig. 6. Result of experiment 1. (a)Transport distance without RCC. (b)Transport distance with RCC. (c)Pitch angle without RCC. (d)Pitch angle with RCC

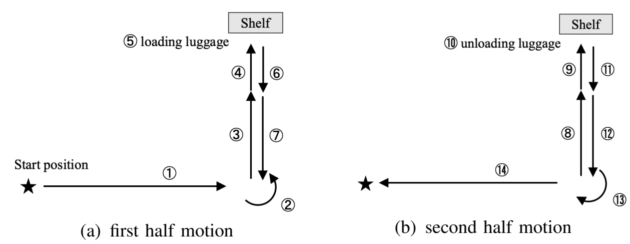


Fig. 7. Motion conducted in experiment 2

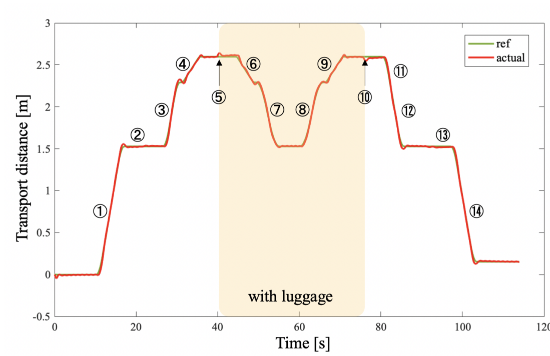
6-9 The machine moves backward and forward with luggage (t=46-72).

10 Arms are driven to automatically unload the luggage(2 kg) onto the shelf (t=76).

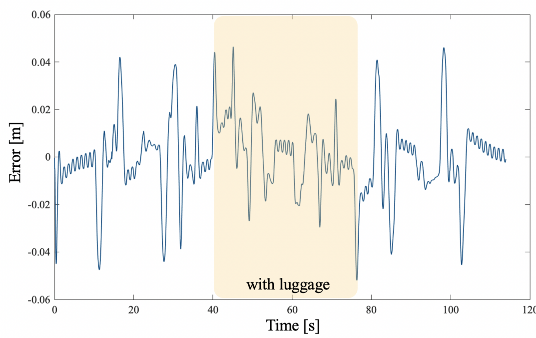
11-14 The machine returns from the shelf to the starting position by moving backward and turning (t=80-120).

Operations 3 and 4 are performed at different speeds, as are 6 and 7, and 8 and 9. This experiment can evaluate all movements, including the accuracy of tracking to the target position with or without luggage, and the automatic loading and unloading of luggage.

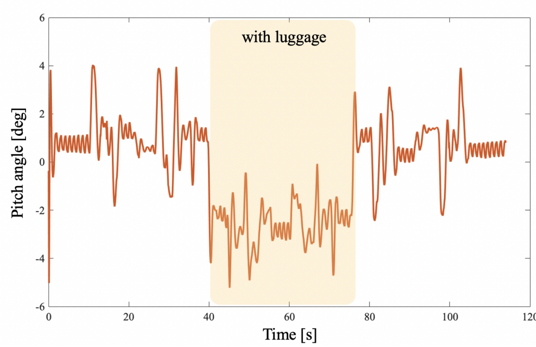
Result: Result of experiment 2 is shown in Fig. 8. Fig. 8(a) shows the transport distance and (b) shows tracking error value, (c) shows pitch angle. In Fig. 8(a), the numbers represent each operation in Fig. 7. In yellow area, the luggage is loaded. Tracking error increases with the timing of operation switching. However, the actual values of transport distance generally follow the reference values regardless of the presence or absence of luggage, and the tracking error is within -0.04 to 0.04 m. It can be said that the error is quite small and positional control has been well achieved. And, since the vehicle body is not destabilized and collapsed at 40 and 76 seconds, it was also realized that the arms were driven and the luggage was automatically loaded and unloaded. Pitch angle changes to a negative value while luggage is on board from 40 to 76 seconds, and RCC compensates for the displacement of the center of gravity due to luggage. From these results, the experiment shows that the proposed method utilizing RCC is appropriate as a position control system.



(a) transport distance



(b) Tracking error



(c) Pitch Angle

Fig. 8. Results of experiment 2

V. CONCLUTION AND FUTURE WORK

In this paper, to establish the stabilization control, Carrying luggage by two-wheeled robot is considered. If the luggage loading position and the center of gravity of the body are misaligned, the pitch angle will be tilted, and the robot continue to move forward and accelerate, and cannot maintain in place. Therefore, we propose to apply Repulsive compliance control to compensate for the constant shift in the center of gravity due to luggage loading. Repulsive compliance control generates a pitch angle command value opposite to the external force due to luggage loading. Due to this, the posture of the robot can be stabilized. Two experiments are conducted. First experiment shows the validity of RCC, and second experiment shows the realization of position tracking and automatic luggage loading and unloading. The experimental results show that RCC is effective in compensating for the constant shift of the center of gravity caused by luggage loading and other factors. In addition, the control design including RCC was sufficient to achieve tracking to the target position.

TABLE II
EXPERIMENT PARAMETERS

Variable	Value	Explanation
K_p	200	P gain of Lyapunov based control
K_d	28.28	D gain of Lyapunov based control
K_{pw}	4.5	P gain for position control
K_{iw}	0.6	I gain for position control
K_{pf}	100	P gain for arm position control
K_{df}	20	D gain for arm position control
ϕ	20	Angle of Phase lead compensator $[\mathrm{rad}]$
g_f	$2\pi \cdot 5$	Cut off freq of arm DOB $[\mathrm{rad/s}]$
g_{fr}	$2\pi \cdot 5$	Cut off freq of arm RTOB $[\mathrm{rad/s}]$
g_s	$2\pi \cdot 4$	Cut off freq of SPADO $[\mathrm{rad/s}]$
A_c	1	Assist gain of RCC
K_c	2.5	Virtual spring of RCC
D_c	0.625	Virtual damper of RCC
M_c	0.04	Virtual mass of RCC

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