Development of Flow Rate Feedback Control in Tilting-ladle-type Pouring Robot with Direct Manipulation of Pouring Flow Rate

Yuta Sueki[a] and Yoshiyuki Noda[b]

Department of Mechanical Engineering, University of Yamanashi, 4-3-11, Takeda, Kofu, 400-8511, Japan

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Abstract: This paper describes the advanced control technology for the tilting-ladle-type pouring robots in the casting industry. In the pouring process in which the molten metal is poured into the pouring basin of the mold by tilting the ladle, it is difficult to pour the molten metal as desired pouring flow rate by the operator. Because the pouring flow rate is manipulated indirectly by manipulating the ladle's angle. In order to solve this problem, in previous studies, we developed the direct manipulation system of the pouring flow rate in the pouring robots. However, the error between the desired and the actual pouring flow rate can be caused by the disturbances in the pouring condition. Therefore, in this study, we develop the pouring flow rate feedback control for improving the tracking performance. In this approach, the pouring flow rate can be estimated by using the extended Kalman filter, and the feedback controller can be constructed by the gain-scheduled PID control based on the estimated flow rate. The developed system is applied to the laboratory-type pouring robot. According to the experiments, the operator can manipulate the pouring flow rate as desired, even in the pouring condition with the disturbance.

1 INTRODUCTION

In the casting industry, the pouring process is dangerous process because the workers use the molten metal which has high temperature. To improve the dangerous working environment, the pouring process has been automated(Lindsay, 1983). In particular, a tilting-ladle-type pouring robot is automated from the handwork in which the molten metal is poured into the pouring basin of the mold, and it is often used in the casting industry since the pouring robot has simple construction and it is easy to change the types of metal. As a control system of the tilting-ladle-type pouring robot, the teaching-and-playback control is often used(Watanabe and Yoshida, 1992), (Yajima and Noda, 2018). In the teaching mode, the operator manipulates the angle of the ladle by using the operational terminal from the remote location. The pouring process requires to pour the molten metal precisely into the pouring basin of the mold without spilling out. However, to satisfy the requirement is difficult, because the operator has to manipulate indirectly the pouring flow rate of the outflow liquid by manipulating the tilting ladle(Voss, 2018). In order to solve this problem, we have developed the direct manipulation system of the pouring flow rate in the tilting-ladle-type pouring robot(Sueki and Noda, 2017a), (Sueki and Noda, 2018) as shown in Figure 1. In these studies, the direct flow rate manipulation system is based on the flow rate feedforward control with the inverse model(Noda and Terashima, 2007). The pouring flow rate feedforward control (Noda and Terashima, 2007) also contributes to the analyses of the falling motion of the outflow liquid from the ladle and development of the falling position control of the outflow liquid to pour accurately the molten metal into the pouring basin(Sueki and Noda, 2017b), (Ito et al., 2012).

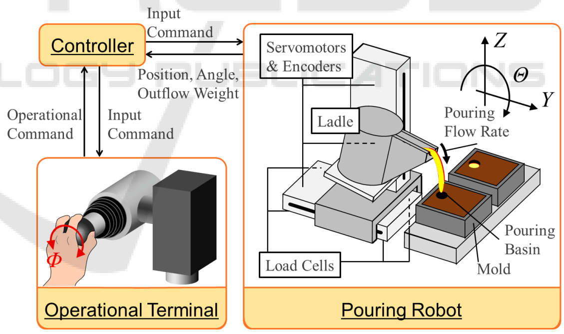

Figure 1: Tilting-ladle-type Pouring Robot.

However, the performance of the tracking to the

[a] https://orcid.org/0000-0002-5972-2425
[b] https://orcid.org/0000-0001-8500-5529

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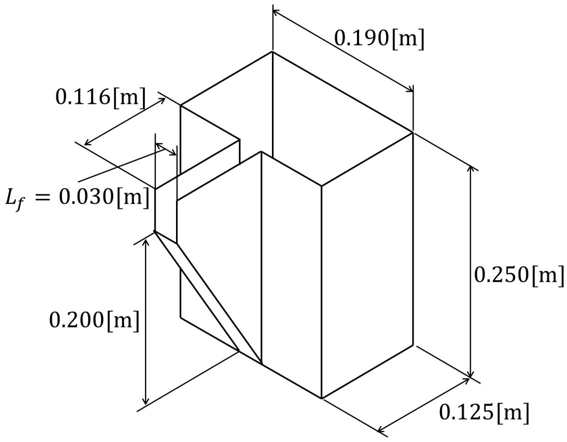


Figure 2: Geometry of Ladle.

desired flow rate can be degraded by some disturbances. As one of the major disturbances in the pouring process, the tilting angle of the ladle at the beginning of the liquid outflow is uncertain by varying the liquid density and the surface tension.

Therefore, in this study, we develop the pouring flow rate feedback control system for suppressing the disturbance in the tilting-ladle-type pouring robot. To construct the pouring flow rate feedback control, the pouring flow rate needs to be measured while pouring. However, it is difficult to measure the pouring flow rate directly by using a flow mater because the sensor will be damaged by the molten metal. Therefore, the extended Kalman filter(Noda et al., 2008), (Noda and Terashima, 2012) is applied to the developed feedback control system to estimate the pouring flow rate in real time. Moreover, we propose the gain-scheduled PID control based on the approximate linearization of the pouring process, since the pouring process is modeled as non-linear model in previous study(Noda and Terashima, 2007). In this feedback control system, the PID parameters are varied in accordance with the pouring state. The developed pouring flow rate feedback control system is applied to the laboratory-type pouring robot and the efficacy of the proposed approach is verified through the experiments.

2 TILTING-LADLE-TYPE POURING ROBOT

In this study, the tilting-ladle-type pouring robot as shown in Figure 1 is used. The ladle can be transferred on Y- and Z-axes and rotated on Θ-direction by servomotors. The driving force of each motor is amplified through a ball-screw mechanism on the Y- and

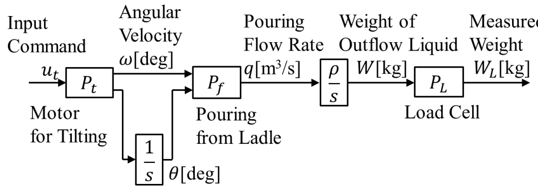


Figure 3: Block Diagram of Pouring Process in Pouring Robot.

Z- axes. The transfer distance and the tilting angle of the ladle can be measured by rotary encoders installed into the motors. The center of the ladle's rotation shaft is placed near the ladle's center of gravity. In case that the ladle is rotated around the center of gravity, the tip of the pouring mouth in the ladle moves in a circular trajectory. It is difficult to pour the molten metal into the pouring basin, since the pouring mouth is moved by tilting. Therefore, the position of the tip of the pouring mouth is controlled invariably while pouring by means of the synchronous control of the Y- and Z- axes for rotational motion around the ladle's Θ-direction(Suzuki et al., 2008). The weight of outflow liquid can be measured by the load cells equipped on the base of the pouring robot. In this study, the ladle shown in Figure 2 which has the trapezoidal shape is used. The target liquid is water for safety reason. As the operational terminal, the joystick is used in this study. The joystick can be rotated for tilting the ladle on Θ-direction. The attitude of the joystick can be measured by the rotary encoder.

3 MATHEMATICAL MODELS OF POURING PROCESS

Figure 3 shows the block diagram of the pouring process which is used in this study. The input command is applied to the motor for tilting the ladle. Then, the liquid is poured from the ladle. The weight of the outflow liquid is measured by the load cell.

3.1 Motor Model

In Figure 3, the motor model P_t for tilting the ladle is simplified as a first-order-lag system described as

$$\frac{d\omega(t)}{dt} = -\frac{1}{T_m}\omega(t) + \frac{K_m}{T_m}u_t(t), \qquad (1)$$

where ω[deg/s] is the angular velocity of the tilting ladle, and u_t is the input command applied to the motor. T_m[s] is the time constant, and K_m[deg/s] is the gain constant. In this study, T_m is 0.022[s] and K_m is 0.980[deg/s].

3.2 Pouring Process Model

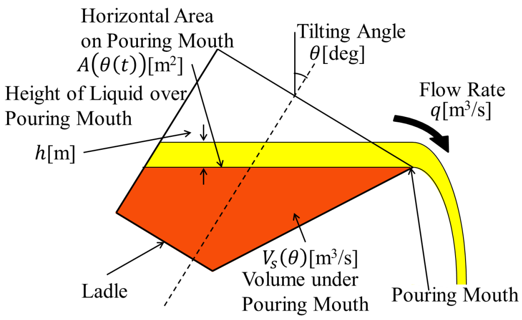


Figure 4: Cross Section of Pouring Process.

The pouring process model P_f in Figure 3 represents the dynamics from the angular velocity ω to the flow rate q[m^3/s] of the outflow liquid. The cross section of the pouring process is shown in Figure 4. In Figure 4, the mass balance of the liquid in the ladle is described as

$$\frac{dV_r(t)}{dt} = -q(t) - \frac{\partial V_s(\theta(t))}{\partial \theta}\omega(t), \quad (2)$$

where V_r[m^3] is the liquid volume over the pouring mouth, and V_s[m^3] is the liquid volume under the pouring mouth. h[m] is the height of the liquid over the pouring mouth. The volume V_r[m^3] can be represented as

$$V_r(t) \approx A(\theta(t))h(t), (h \geq 0), \quad (3)$$

where, A[m^2] is the upper surface of the liquid in the ladle. As seen from Figure 4, the surface A is changed by tilting angle θ[deg] of the ladle.

By using Bernoulli's principle, the flow rate q at the liquid height h[m] shown as

$$q(t) = c\int_0^{h(t)} L_f(h_a)\sqrt{2gh_b}\,dh_b, \quad (4)$$
$$(0 < c \leq 1, h_a = h(t) - h_b),$$

where L_f[m] is the width of the pouring mouth at the height h_a[m] from the bottom edge of the pouring mouth as shown in Figure 5, and h_b[m] is the depth at the pouring mouth from the surface of the liquid in the ladle. c is the flow rate coefficient, which can be identified by the comparison of the experimental result of the measured liquid weight and the simulated result of the load cell model. In this study, c is 0.75. g[m/s^2] is the acceleration of gravity.

From Eqs. (2), (3) and (4), the dynamics of the liquid height over the pouring mouth in the pouring process can be derived as

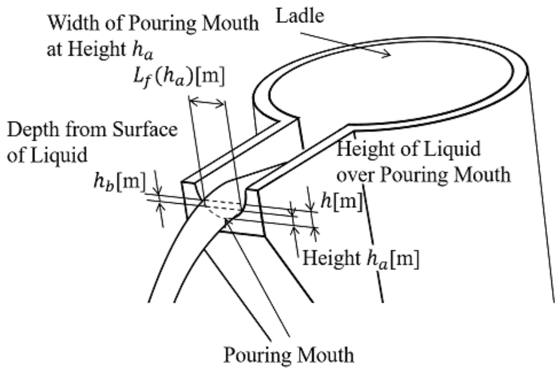


Figure 5: Parameters on Pouring Mouth.

$$\frac{dh(t)}{dt} = -\frac{q(h(t))}{A(\theta(t))} - \frac{1}{A(\theta(t))}\left(\frac{\partial A(\theta(t))}{\partial\theta(t)}h(t) + \frac{\partial V_s(\theta(t))}{\partial\theta(t)}\right)\omega(t). \quad (5)$$

3.3 Load Cell Model

The actual weight W[kg] of the outflow liquid can be represented as

$$\frac{dW(t)}{dt} = \rho q(t), \quad (6)$$

where ρ[kg/m^3] is the density of the liquid. The dynamics of the load cell can be simplified as a first-order-lag system. Therefore, the load cell model P_L is described as

$$\frac{dW_L(t)}{dt} = -\frac{1}{T_L}W_L(t) + \frac{1}{T_L}W(t), \quad (7)$$

where W_L[kg] is the weight of the outflow liquid measured by the load cell, and T_L[s] is the time constant of the load cell. In this study, T_L is 0.16[s].

4 POURING FLOW RATE ESTIMATION

In this study, the state estimation is decentralized to the motor system and the pouring process(Noda and Terashima, 2012). In the state estimation approach, a steady-state Kalman filter is applied to the motor model for estimating the angular velocity of the ladle and an extended Kalman filter is applied to the pouring process with the load cell model from the angular velocity of the ladle to the measured weight by the load cell for estimating the pouring flow rate.The discrete-time steady-state Kalman filter(Noda and Terashima, 2012) is applied to the discrete-time state equation of the motor model described as

$$\begin{bmatrix} \omega_{n+1} \\ \theta_{n+1} \end{bmatrix} = \begin{bmatrix} 1-\frac{T_s}{T_m} & 0 \\ T_s & 1 \end{bmatrix} \begin{bmatrix} \omega_n \\ \theta_n \end{bmatrix} + \begin{bmatrix} \frac{T_s K_m}{T_m} \\ 0 \end{bmatrix} u_{tn}, \quad (8)$$

$$y_n = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} \omega_n \\ \theta_n \end{bmatrix}, \quad (9)$$

where, T_s[s] represents the sampling interval and it is determined 0.020[s] in this study. By applying the estimated angular velocity $\bar{\omega}$[deg/s] to the pouring process model, the pouring flow rate can be estimated.

To estimate the pouring flow rate, we used the discrete-time extended Kalman filter(Noda and Terashima, 2012). The discrete-time extended Kalman filter is applied to the discrete-time state equation can be represented as

$$x_{n+1} = f(x_n), \quad (10)$$
$$y_n = \eta(x_n), \quad (11)$$

where,

$$x = \begin{bmatrix} h & W & W_L \end{bmatrix}^{\mathrm{T}}, \quad (12)$$

$$f(x) = \begin{bmatrix} \left(1-\frac{T_s}{A(\theta)}\frac{\partial A(\theta)}{\partial \theta}\bar{\omega}\right)h \\ -\frac{T_s q(h)}{A(\theta)}\bar{\omega} - \frac{T_s}{A(\theta)}\frac{\partial V_s(\theta)}{\partial \theta}\bar{\omega} \\ W + T_s \rho q(h) \\ (1-\frac{T_s}{T_L})W_L + \frac{T_s}{T_L}W \end{bmatrix}, \quad (13)$$

$$\eta(x) = W_L. \quad (14)$$

Then, the estimated pouring flow rate $\bar{q}$[m^3/s] can be obtained from the estimated liquid height $\bar{h}$[m] as

$$\bar{q}(\bar{h}(t)) = c\int_0^{\bar{h}(t)} L_f(h_a)\sqrt{2gh_b}\,dh_b. \quad (15)$$

5 POURING FLOW RATE FEEDBACK CONTROL

The pouring flow rate feedback control system in the tilting-ladle-type pouring robot with direct manipulation of flow rate is shown as Figure 6. In Figure 6, the operational angle of joystick is applied to the pouring flow rate feedforward controller(Sueki and Noda, 2018) which is based on the inverse model of the pouring process. Then, the reference trajectory and the reference input can be generated. In other words, the 2-DOF flow rate control system is constructed by integrating the flow rate feedforward and feedback control systems.

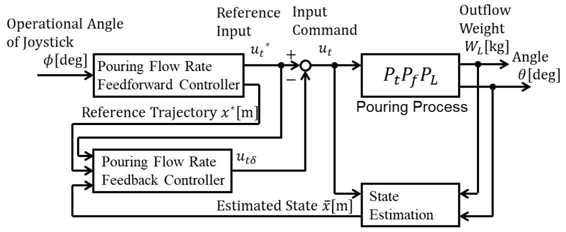


Figure 6: Block Diagram of Pouring Flow Rate Feedback Control in Operational Pouring Robot with Manipulatable Pouring Flow Rate.

5.1 Approximate Linearization of Pouring Process

The pouring process model in the previous study(Noda and Terashima, 2007) is the nonlinear model described as Eq. (5). Therefore, the poring process model is linearized approximately to design the feedback control system. In particular, the state equation of the liquid height in the pouring process is linearized approximately around the operating point. The mathematical model of the pouring process can be represented as

$$x = h,\ \dot{x} = f(x,u_t), \quad (16)$$

$$f(x,u_t) = -\frac{q(h)}{A(\theta)} - \frac{1}{A(\theta)}\left(\frac{\partial V_s(\theta)}{\partial \theta} + \frac{\partial A(\theta)}{\partial \theta}h\right)K_m u_t. \quad (17)$$

the partial derivatives of state x and input command u_t are described respectively as

$$\frac{\partial f(x,u_t)}{\partial x} = -\frac{1}{A(\theta)}\frac{\partial q(h)}{\partial h} - \frac{1}{A(\theta)}\frac{\partial A(\theta)}{\partial \theta}K_m u_t, \quad (18)$$

$$\frac{\partial f(x,u_t)}{\partial u_t} = -\frac{1}{A(\theta)}\left(\frac{\partial V_s(\theta)}{\partial \theta} + \frac{\partial A(\theta)}{\partial \theta}h\right)K_m. \quad (19)$$

By using the deviations x_δ, $u_{t\delta}$ around the operating point, the approximate linearized pouring process model can be represented as

$$\dot{x_\delta} = A_x(x^*,u_t^*)x_\delta + B_x(x^*,u_t^*)u_{t\delta}, \quad (20)$$
$$A_x(x^*,u_t^*) = \left.\frac{\partial f(x,u_t)}{\partial x}\right|_{x=x^*,u_t=u_t^*},$$
$$B_x(x^*,u_t^*) = \left.\frac{\partial f(x,u_t)}{\partial u_t}\right|_{x=x^*,u_t=u_t^*},$$
$$x_\delta = x - x^*,\ u_{t\delta} = u_t - u_t^*, \quad (21)$$

where, x^* and u_t^* mean the reference trajectory and the input command for realizing the reference trajectory, respectively.

5.2 Gain-scheduled PID Control

In this section, the gain-scheduled PID control which has the variable gains corresponding to the pouring state is derived. The control law is described as

$$u_{t\delta} = -K_P(x^*, u_t^*)x_\delta - K_I(x^*, u_t^*)\int x_\delta dt - K_D \dot{x}_\delta. \quad (22)$$

By substituting Eq. (22) to Eq. (20), the state equation can be represented as

$$\begin{aligned}\dot{x_\delta} &= A_x(x^*, u_t^*)x_\delta - B_x(x^*, u_t^*)K_P(x^*, u_t^*)x_\delta \\ &\quad -B_x(x^*, u_t^*)K_I(x^*, u_t^*)\int x_\delta dt - B_x(x^*, u_t^*)K_D\dot{x}_\delta, \quad (23)\end{aligned}$$

where, K_P, K_I and K_D are the proportional gain, the integral gain and the derivative gain respectively. Then, a new variable $z = \int x_\delta dt$ is defined and the state equation for z can be represented as

$$\begin{aligned}\frac{d}{dt}\begin{bmatrix} z \\ \dot{z} \end{bmatrix} &= A_z(x^*, u_t^*)\begin{bmatrix} z \\ \dot{z} \end{bmatrix}, \quad (24)\\ A_z(x^*, u_t^*) &= \begin{bmatrix} 0 & 1 \\ a_{z21} & a_{z22} \end{bmatrix}, \\ a_{z21} &= -\frac{B_x(x^*, u_t^*)K_I(x^*, u_t^*)}{1 + B_x(x^*, u_t^*)K_D}, \\ a_{z22} &= \frac{A_x(x^*, u_t^*) - B_x(x^*, u_t^*)K_P(x^*, u_t^*)}{1 + B_x(x^*, u_t^*)K_D}.\end{aligned}$$

The characteristic equation of Eq. (24) is described as

$$s^2 - a_{z22}s - a_{z21} = 0. \quad (25)$$

The generalized form of second-order-lag system can be represented as

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0, \quad (26)$$

where, ω_n[rad/s] is a natural angular frequency and ζ is a damping ratio. Then, the pole s can be derived as

$$s = -\zeta\omega_n \pm \omega_n\sqrt{1 - \zeta^2}i. \quad (27)$$

By comparing Eq. (25) with Eq. (26), PID parameters can be derived as

$$\begin{aligned}K_P(x^*, u_t^*) &= \frac{A_x(x^*, u_t^*) + 2\zeta\omega_n}{B_x(x^*, u_t^*)} \\ &\quad -2\zeta\omega_n K_D, \quad (28)\\ K_I(x^*, u_t^*) &= \frac{\omega_n^2}{B_x(x^*, u_t^*)} + \omega_n^2 K_D, \quad (29)\\ K_D &= \text{const.} \quad (30)\end{aligned}$$

In this study, PID parameters are designed by the pole assignment method. The criteria for deciding the poles of Eq. (24) are the following:

- The real parts of the poles should be negative;
- The system should not vibrate;
- It is possible to apply the generated input command by PID controller to the controlled object.

Depending on these criteria, we obtained $s = -2.0 \pm 0i$ and the parameters included in s are $\omega_n = 2.0$[rad/s] and $\zeta = 1.0$ in this study.

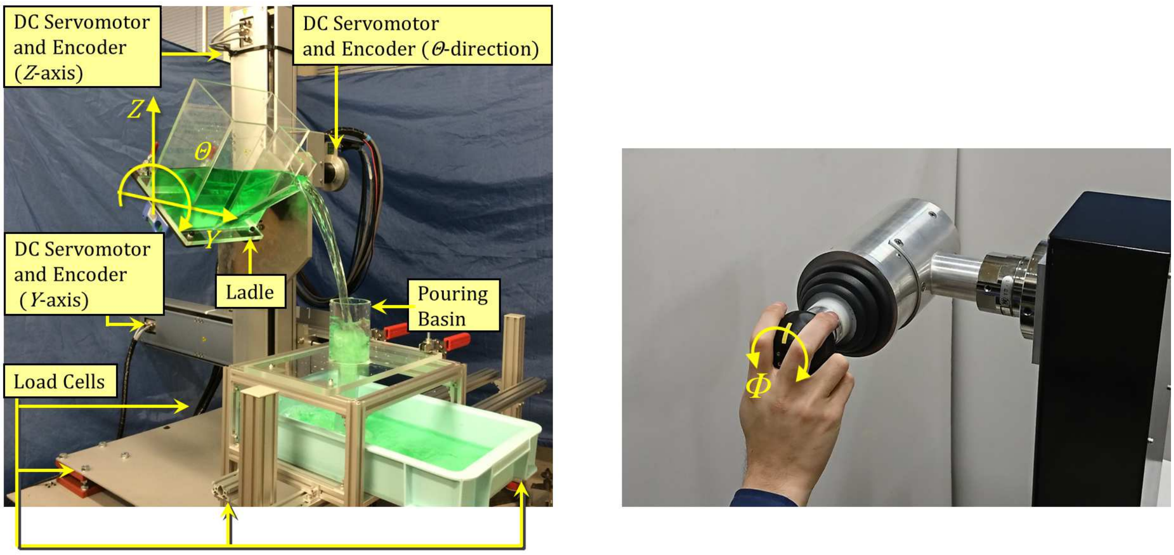
In the PID parameters, the proportional gain K_P and the integral gain K_I can be obtained uniquely, and the derivative gain K_D can be decided arbitrarily. To obtain K_D which can be implemented to the pouring robot, K_D is applied to the pouring robot and steadily increased. In this study, it was confirmed that the experimental equipment vibrated in case that K_D was applied. Because K_D can increase the noise depending on the measured weight by the load cell. Thus, the derivative gain is obtained as $K_D = 0$ and this condition means that PI controller is constructed as the feedback controller for the experimental verification.

6 EXPERIMENTAL VERIFICATION

Figure 7 shows the laboratory-type pouring robot used in this study. The operator uses the joystick as shown in Figure 7(b) as the operational terminal. By rotating the joystick in Φ- direction, the liquid is poured from the ladle.

6.1 Direct Manipulation of Pouring Flow Rate

The direct manipulation of pouring flow rate is applied to the laboratory-type pouring robot and the efficacy of this manipulation approach is verified in the ideal condition which is without the disturbances. In other words, the direct manipulation system is constructed with the flow rate feedforward controller and without flow rate feedback controller. Also, the direct manipulation of pouring flow rate is compared with the ladle's angular velocity control which is used in practical conditions. In the experiments, the operator try to pour the liquid as steady flow rate. The results of the pouring motion with the angular velocity control and with the proposed approach are shown in Figures 8 and 9 respectively. Figure 8(a) shows the operational angle of joystick. (b) shows the angular velocity of the ladle estimated by using the steady-state Kalman filter. (c) shows the tilting angle of the ladle measured by the encoder. (d) and (e) show the liquid height on the pouring mouth of the ladle and the pouring flow rate respectively. The dashed lines are the simulated results obtained by applying above



(a) Pouring Robot (b) Joystick

Figure 7: Laboratory-type Pouring Robot.

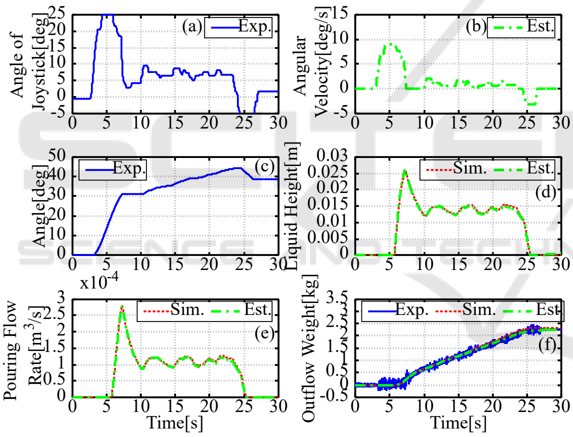


Figure 8: Experimental Results of Pouring Motion with Angular Velocity Manipulation.

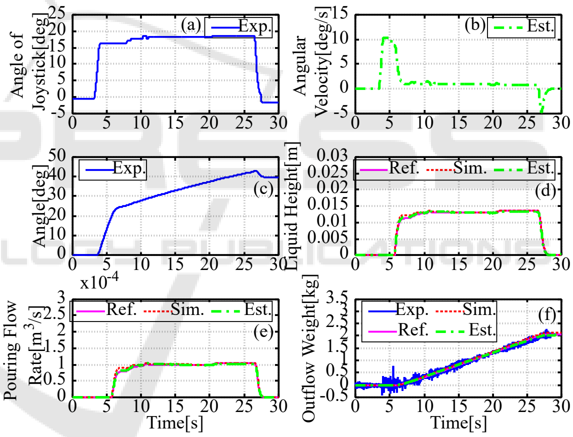


Figure 9: Experimental Results of Pouring Motion with Direct Manipulation of Pouring Flow Rate without flow rate feedback control.

results (b) and (c) to Eq. (5). The chained lines are the estimated results by using the extended Kalman filter(EKF). Figure 8(f) shows the weight of the outflow liquid. The blue solid line is the measure result by using the load cell and the other lines are in the same manner as (d) and (e). In Figure 9(d), (e) and (f), the magenta solid lines are the reference value designed before pouring. The other lines are shown in the same manner as Figure 8. According to Figure 8, it is shown that the operator manipulated the angular velocity of the ladle by using the joystick and indirectly manipulated the pouring flow rate. On the other hand, Figure 8 shows that the pouring flow rate is similar to the operational angle of the joystick. From these results, it was confirmed that the operator can manipulate the pouring flow rate directly and pour the liquid as steady flow rate by using the developed system.

6.2 Flow Rate Feedback Control with Direct Manipulation of Pouring Flow Rate

The pouring flow rate feedback control system shown as Figure 6 is applied to the laboratory-type pouring robot as shown in Figure 7. In the experiments, the ideal angle of the ladle at the beginning of the liquid outflow is 20[deg]. However, the beginning of

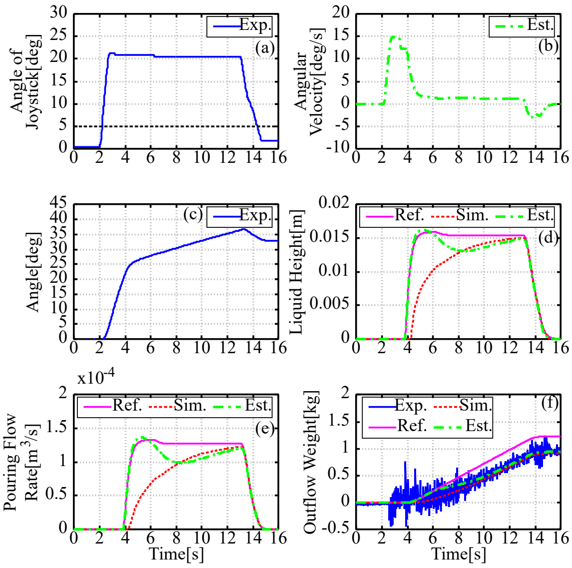


Figure 10: Experimental Results of Pouring Motion with only Flow Rate Feedforward Control in Previous Approach.

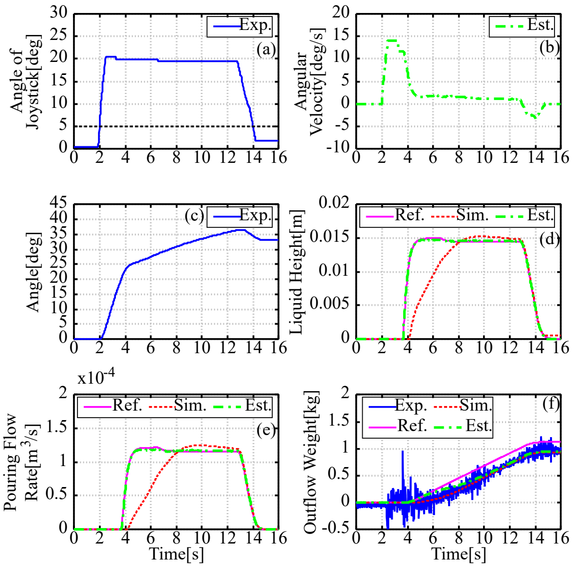


Figure 11: Experimental Results of Pouring Motion with Flow Rate Feedback Control and Flow Rate Feedback Control in Proposed Approach.

liquid outflow is delayed by the disturbance which is similar to the practical condition. To create the disturbance, the actual volume of the liquid in the ladle is less than with the ideal volume. The ideal volume means the volume in case that the liquid in the ladle can be poured at the ideal angle. Thus, the tilting angle of the ladle at the beginning of the liquid outflow is larger than the ideal angle. In this study, the error of the tilting angle of the ladle at the beginning of the liquid outflow is +3[deg] and this error is caused by the disturbance.

Figures 10 and 11 are the results of the pouring motion with and without the pouring flow rate feedback control system respectively. In addition, Figures 10 and 11 are shown in the same manner as Figure 9. According to the results in case without the pouring flow rate feedback control system as shown in Figure 10(e), the simulated pouring flow rate was not able to reach the reference pouring flow rate until near the 13[s] mark in time-series data. On the other hand, Figure 11(d) in case with the pouring flow rate feedback control system shows that the simulated pouring flow rate was able to reach the reference pouring flow rate near the 8[s] mark. Then, the simulated result tracked the reference value.

7 CONCLUSIONS

In this study, we developed the pouring flow rate feedback control in the tilting-ladle-type pouring robot with direct manipulation of pouring flow rate. In the developed system, the extended Kalman filter is applied to estimate the pouring flow rate in real time. To construct the feedback control system, the approximate linearization model of the pouring process is derived since the mathematical model of the pouring process has non-linear system. By using the approximate linearization model, we proposed the gain-scheduled PID control which has variable gain depending on the pouring state. In this approach, PID parameters can be designed by the pole assignment method. The developed feedback control system was applied to the laboratory-type pouring robot to verify the efficacy of the proposed approach. In the experiments, firstly, we demonstrated that the efficacy of the direct manipulation of the pouring flow rate, and it was shown that the operator can manipulate the pouring flow rate as desired. Then, the pouring flow rate feedback control is applied to the pouring robot and the efficacy is verified. Through the experiments, it was confirmed that the pouring flow rate can track the desired flow rate by the operator even in the condition with disturbance.

In our future work, in order to operate more easily and safely the tilting-ladle-type pouring robot with the direct manipulation system of the pouring flow rate, a suitable interface between the operator and the pouring robot will be developed.

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