Implementation of Push Recovery Strategy Using Triple Linear Inverted Pendulum Model in “T-FloW” Humanoid Robot

R. Dimas Pristovani, D. Raden Sanggar, Pramadihanto. Dadet
EEPIIS Robotics Research Center (ER2C), Politeknik Elektronika Negeri Surabaya (PENS), Indonesia

E-mail: *dimaspens@gmail.com, sanggar@pens.ac.id, dadet@pens.ac.id

Abstract. Push recovery is one of human behavior which is a strategy to defend the body from an external force in any environment. This paper describes push recovery strategy which uses MIMO decoupled control system method. The dynamics system uses a quasi-dynamic system based on triple linear inverted pendulum model (TLIPM). The analysis of TLIPM uses zero moment point (ZMP) calculation from ZMP simplification in last research. By using this simplification of dynamics system, the control design can be simplified into 3 serial SISO with known and uncertain disturbance models in each inverted pendulum. Each pendulum has different plan to damp the external force effect. In this experiment, PID controller (closed-loop) is used to arrange the damping characteristic. The experiment result shows that when using push recovery control strategy (closed-loop control) is about 85.71% while without using push recovery control strategy (open-loop control) it is about 28.57%.

1. Introduction
Push recovery challenge has the main goal, which withstands a strong push and keeps standing. The robot receives a push from an object that swings against its body. The robot receives one or more pushes and withstands successfully to fulfill the push recovery challenge [1]. The humanoid robot in this discussion is called “T-FloW”. In this discussion, we use a T-FloW humanoid robot with 28 Degrees of Freedom (DoF) version. To complete the push recovery challenge, the MIMO decoupled control system analysis is used to design the control system [2–3]. Another research about push recovery is also using similar action [11–21], but the difference in this discussion is the dynamics system approach and control system. With a lot of DoF, the dynamics model of T-FloW is approached by using Triple Linear Inverted Pendulum Model (TLIPM) [4–5].

With this approach, the dynamics system model of T-FloW will be quasi-dynamics system model and its analyzed by using the calculation of zero moment point (ZMP) analysis as in the previous research [6–8]. By using this simplification of dynamics system, the control design can be simplified into 3 serial SISO with known and uncertain disturbance (mass and external force) in each inverted pendulum (IP). Each pendulum has different plan to damp the external force effect (uncertain disturbance). In this plan, PID controller is used to arrange the damping characteristic [9–10]. In the experiment result will explaining about the comparison between open-loop push recovery control.
strategy (without PID controller) and closed-loop (3 serial SISO) push recovery control strategy (with PID controller).

2. Originality
The differences with previous research about push recovery strategy are in the dynamics system approach and control system usage. As mentioned before, the dynamics system approach is using Triple Linear Inverted Pendulum Model (TLIPM). In previous research in reference [11-21], they are using Double Linear Inverted Pendulum Model (DLIPM) or Single Linear Inverted Pendulum Model (SLIPM). The control system design is using MIMO decoupled control system analysis with PID controller. This proposed control system is used to smoothing the movement of each IP. In another research in reference [11-21], they are not using MIMO control analysis. The last difference is in the domain input for the control system. In our control system is using cartesian space input for the control system and another research is using joint space input for their control system.

3. Mechanical Design (T-FLoW)
Mechanical design of T-FLoW humanoid robot is shown in figure 1. T-FLOW humanoid robot has 2 version of mechanical design which is using 28 Degree of Freedom (DoF) and using 38-DoF. But, in this discussion, 28-DoF version of T-FLoW humanoid robot will be used. The configuration of 28-DoF is 16-DoF in the left and right leg, 3-DoF in the waist, 6-DoF in the left and right arm, and 3-DoF in the head. The total height and width of T-FLoW humanoid robot are about 112.67cm and 27.54cm. The configuration of each joint and number of actuators are shown in table 1.

![Figure 1. 28-DoF version mechanical design of T-FLoW humanoid robot.](image)

| Parts   | Degree of Freedom | Number of Actuator |
|---------|------------------|--------------------|
| Head    | 3                | 3                  |
| Right Arm | 3              | 3                  |
| Left Arm | 3                | 3                  |
| Waist   | 3                | 4                  |
| Right Leg | 8              | 9                  |
The lower body is a left leg, right leg, and hip. T-FLoW humanoid robot using parallel link mechanical system called parallelogram mechanism in the left and right legs. The parallelogram mechanism is used to add more active torque in the legs. The upper body is a left arm, right arm, and waist. The upper body is using serial link mechanical system.

4. Quasi Dynamics System Model
In the last research of T-FLoW humanoid robot, ZMP classic calculation was used to obtain the dynamics characteristic. Where \( \mathbf{P}_{\text{zmp,}(x,y,z)} = [P_{\text{zmp,x}}, P_{\text{zmp,y}}, P_{\text{zmp,z}}]^T \) is position vector of ZMP from its origin position. The main equation to calculate the position vector of ZMP for multi-body is shown in Equation 1 as follows:

\[
\mathbf{P}_{\text{zmp,}(x,y)} = \mathbf{P}_{\text{CoM,}(x,y)} m_{\text{tot}} g_z + \mathbf{P}_{\text{zmp,}(x,y)} \mathbf{\dot{P}}(x,y) - \mathbf{\dot{L}}(y,x) / m_{\text{tot}} g_z + \mathbf{\ddot{P}}_z
\]

In which \( \mathbf{P}_{\text{CoM,}(x,y,z)} \) is the position vector of CoM. This position can be obtained from position calculation of each joint, which is used in the robot. \( \mathbf{P}_{\text{zmp,}(x,y,z)} \) is the position vector of ZMP. This position is the dynamics characteristic of the system. \( m_{\text{tot}} \) is the mass total from the system. \( \mathbf{\dot{L}}(x,y,z) \) and \( \mathbf{\dot{P}}(x,y,z) \) is the angular acceleration (torque) and the linear acceleration (force). \( g_z \) is the linear acceleration of gravitation in Z axis. When discussing control system, the dynamics system must be calculated in real time condition. Because of it, the dynamic system model of T-FLoW humanoid robot is approached by using Triple Linear Inverted Pendulum Model (TLIPM). The simplification design of dynamic system model based on TLIPM is shown in figure 2.

![Figure 2. Part division of TLIPM in T-FLoW humanoid robot which is Head part (IP 1), Trunk part (IP 2), and Leg part (IP 3).](image-url)
Legs part (IP 3).

The dynamics calculation of T-FLoW humanoid robot is divided into 3 parts which are Head part (IP 1), Trunk part (IP 2), and Legs part (IP 3). As mentioned before, the dynamics system is simplified from multi-body analysis into single body analysis based on the parts. Because of it, the position vector of ZMP for multi-body in Equation 1 from previous research is developed and simplified to obtain dynamics system based on Inverted Pendulum (IP) model.

\[
P_{zmp, (x,y,z)} = \begin{bmatrix} P_{zmp, x} & P_{zmp, y} & 0 \end{bmatrix}^T
\]

The explanation from Equation (2) and (3) above is included in Equation (1). In the IP models, the linear acceleration in Z axis is equal to zero \((P_{CoM, z} = 0)\) and \(g_{(x,y,z)} = [0 \ 0 \ -g_z]^T\) (the gravitational acceleration vector).

\[
P_{zmp, (x,y,z)} = \begin{bmatrix} \frac{m_{tot} g_z + P_{CoM, (x,y,z)}}{m_{tot} g_z + m_{tot} P_{CoM, z}} \\ \frac{m_{tot} g_z + m_{tot} P_{CoM, z}}{m_{tot} g_z + m_{tot} P_{CoM, z}} \\ \frac{m_{tot} g_z + m_{tot} P_{CoM, z}}{m_{tot} g_z + m_{tot} P_{CoM, z}} \end{bmatrix}
\]

Equation (8) is the dynamics model of linear IP. This equation is used to calculate dynamics characteristic in each IP from dynamics system model in T-FLoW humanoid robot. Figure 3, figure 4, and figure 5 is transformation process from multi-body calculation into single body calculation.

**Figure 3.** Mass and position distribution in inverted pendulum 1 (IP 1 – Head part), using 3 DoF.
Figure 4. Mass and position distribution in inverted pendulum 2 (IP 2 – Trunk part), using 9 DoF.

Based on figure 3, figure 4, and figure 5, the position vector of ZMP for each IP can be calculated by using the equation as follows.
\[
P_{H,\text{CoM}(x,y,z)} = \sum_{i=1}^{n=3} m_{H,i}P_{H,i}(x,y,z)
\]

\[
P_{T,\text{CoM}(x,y,z)} = \sum_{i=1}^{n=9} m_{T,i}P_{T,i}(x,y,z) + P_{H,\text{CoM}(x,y,z)}
\]

\[
P_{L,\text{CoM}(x,y,z)} = \sum_{i=1}^{n=16} m_{L,i}P_{L,i}(x,y,z) + P_{T,\text{CoM}(x,y,z)}
\]

\[
P_{(H,T,L)\text{Zmp},(x,y)} = P_{(H,T,L),\text{CoM}(x,y)} - \left(P_{(H,T,L),\text{CoM}(x,y)} / g_{z}\right)\hat{P}_{(H,T,L),\text{CoM}(x,y)}
\]

Where \( H \) is the head part notation, \( T \) is the trunk part notation, and \( L \) is the legs part notation, \( P_{H,\text{CoM}(x,y,z)} \) and \( P_{T,\text{CoM}(x,y,z)} \) and \( P_{L,\text{CoM}(x,y,z)} \) is the position vector of CoM in each IP, \( m_{H,i} \), \( m_{T,i} \) and \( m_{L,i} \) is each joint mass in each IP, \( P_{H,i}(x,y,z) \), \( P_{T,i}(x,y,z) \), and \( P_{L,i}(x,y,z) \) is each joint position vector in each IP. This position vector can be obtained from forward kinematic (FK) analysis, \( \hat{P}_{H,\text{CoM}(x,y)} \), \( \hat{P}_{T,\text{CoM}(x,y)} \), and \( \hat{P}_{L,\text{CoM}(x,y)} \) is linear acceleration of CoM in each IP, this linear acceleration can be obtained from acceleration sensor, \( P_{H,\text{Zmp},(x,y)} \), \( P_{T,\text{Zmp},(x,y)} \), and \( P_{L,\text{Zmp} ,(x,y)} \) is position vector of ZMP in each IP.

5. Control Design Based on System Model

As mentioned in the introduction, T-FLoW humanoid robot is doing a push recovery challenge. The push recovery strategy is adapting the human behavior. When human receives a small external force, they are only correcting the position of their body. The position correction is happening based on the force direction vector. When an external force has X direction (forward direction) and the external force is directly contacting to the upper body of the human, the human reaction is moving the upper body (trunk) into the same direction vector of external force and the legs are moving into the opposite direction vector of external force. This reaction is adapted by T-FLoW humanoid robot. As seen in figure 6, the T-FLoW humanoid robot is receiving an external force through the upper body (trunk). The upper body (trunk) of the robot is following the direction vector of external force. But, the legs and the head body is following the opposite direction vector of external force.
The strategy to damp the external force is how to arrange the position vector of CoM in each IP to not be outside of support polygon (SP). For the first IP, the strategy is how to maintain the condition at the angular position reference which is the first IP is remaining in upright condition ($\theta_{H,P,Ref} = 0$). For second IP, the strategy is how to damp the external force disturbance because the external force is directly contacted with the second IP. In the second IP (Trunk), the arms are used to shift the position vector of CoM in the Trunk. For the third IP (Legs), the strategy is how to compensate the second IP during external force. The compensation is happened because the third IP is the most important part of the robot which is the main base of the robot body.

The MIMO decoupled control design based on system model is used in push recovery control strategy. As mention it before, the dynamic system of T-FLoW humanoid robot is using quasi-dynamic system model approach based on TLIPM.

With this approach, the MIMO decoupled control design is simplified into 3 serial SISO control when implemented into the system. Basically, the MIMO control system example is described in Equation 13 and MIMO decoupled control system which is multi SISO control system example is described in the Equation 14.

$$
\begin{bmatrix}
P_1(t) \\
P_2(t) \\
\vdots \\
P_q(t)
\end{bmatrix}
= 
\begin{bmatrix}
P_{1,1,mp}(t) & P_{1,2,mp}(t) & \cdots & P_{1,p,mp}(t) \\
P_{2,1,mp}(t) & P_{2,2,mp}(t) & \cdots & P_{2,p,mp}(t) \\
\vdots & \vdots & \ddots & \vdots \\
P_{q,1,mp}(t) & P_{q,2,mp}(t) & \cdots & P_{q,p,mp}(t)
\end{bmatrix}
\begin{bmatrix}
U_1(t) \\
U_2(t) \\
\vdots \\
U_p(t)
\end{bmatrix}
$$

or,

$$
\theta(t) = P_{mp}(t)U(t)
$$

(13)

$$
\begin{bmatrix}
P_1(t) \\
P_2(t) \\
\vdots \\
P_q(t)
\end{bmatrix}
= 
\begin{bmatrix}
P_{1,1,mp}(t) & 0 & \cdots & 0 \\
0 & P_{2,2,mp}(t) & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & P_{q,p,mp}(t)
\end{bmatrix}
\begin{bmatrix}
U_1(t) \\
U_2(t) \\
\vdots \\
U_p(t)
\end{bmatrix}
$$

or,

$$
\begin{bmatrix}
P_1(t) \\
P_2(t) \\
\vdots \\
P_q(t)
\end{bmatrix}
= 
\begin{bmatrix}
P_{1,1,mp}(t) & U_1(t) \\
P_{2,2,mp}(t) & U_2(t) \\
\vdots & \vdots \\
P_{q,p,mp}(t) & U_p(t)
\end{bmatrix}
$$

(14)

Based on equation 12, The design of the control system (closed-loop) in the T-FLoW humanoid robot can be seen in figure 6 and the strategy to damping the external force is shown in figure 5. From
figure 6, the total SISO control system (closed-loop) in this system is 6 part such as \( U_{H,x}(t), U_{H,y}(t), U_{T,x}(t), U_{T,y}(t), U_{L,x}(t), \) and \( U_{L,y}(t) \). But, these 6 parts of SISO control system is categorized into 3 IP parts which is first IP (Head) is \( U_{H,x}(t) \) and \( U_{H,y}(t) \), second IP (Trunk) is \( U_{T,x}(t) \) and \( U_{T,y}(t) \), and third IP (Legs) is \( U_{L,x}(t) \) and \( U_{L,y}(t) \).

The control system is work based on cartesian data input from dynamics system calculation. The input is position vector of ZMP \( P_{(H,T,L),zmp,(x,y)} \). The data input is compared with real position vector of each IP \( P_{(H,T,L),real,(x,y)} \) and obtain the position vector error \( e_{(H,T,L),(x,y)} \). The position vector error \( e_{(H,T,L),(x,y)} \) is the input for PID controller \( U_{(H,T,L),(x,y)} \). The PID controller \( U_{(H,T,L),(x,y)} \) has output position vector for the system \( P_{(H,T,L),zmp,(x,y)}^T \), this position vector is used as a new data input in the T-FLoW humanoid robot. Because the data input is in the cartesian area (position vector), it must be transformed into joint area (angle joint) by using Inverse Kinematics (IK) of TLIPM. The Mechanical System (MS) is interference with uncertain disturbance (external force \( Q_{(H,T,L),(x,y)} \)) in each inverted pendulum (IP). To obtain the real-time condition of T-FLoW humanoid robot during external force (TLIPM), The Feedback System (FS) is used to measure it. The FS has several sensors to measure the data of T-FLoW humanoid robot during external force such as angular position (joint area). The feedback must be transformed into cartesian area by using Forward Kinematics (FK) of TLIPM and then this data is already to processed again. The control diagram of push recovery strategy is shown in figure 7 as follows.

\[
P_{(H,T,L),zmp,(x,y)} \rightarrow e_{(H,T,L),(x,y)} \rightarrow U_{(H,T,L),(x,y)} \rightarrow P_{(H,T,L),zmp,(x,y)}^T \rightarrow Q_{(H,T,L),(x,y)} \rightarrow P_{(H,T,L),real,(x,y)} \rightarrow FK_{TLIPM} \rightarrow \theta_{(H,T,L),CoM,(P,R)} \rightarrow IK \rightarrow MS \rightarrow FS \rightarrow PLANT
\]

**Figure 7. TLIPM with serial SISO control system design using PID controller in push recovery strategy.**

The IK process is calculating the local transformation calculation in each IP. From position vector of ZMP in each IP, the angular position in each IP is obtained by using Equation 15.

\[
\theta_{(H,T,L),zmp,(P,R)} = \tan^{-1} \left( \frac{P_{(H,T,L),zmp,(x,y)}^T}{P_{(H,T,L),CoM,(x,y)}} \right)
\]  

(15)

The FK process is similar to IK process, just calculating the local transformation calculation in each IP. From an angular position in each IP, the real position vector in each IP is obtained by using Equation 16 as follows.

\[
P_{(H,T,L),real,(x,y)} = P_{(H,T,L),CoM,(x,y)} \times \sin \theta_{(H,T,L),CoM,(P,R)}
\]

(16)

Where, \( \theta_{H,zmp,(P)} \), \( \theta_{T,zmp,(P)} \), and \( \theta_{L,zmp,(P)} \) is the angular ZMP position transformation result from position vector of ZMP in each IP with pitch rotation. \( \theta_{H,zmp,(R)} \), \( \theta_{T,zmp,(R)} \), and \( \theta_{L,zmp,(R)} \) is the angular ZMP position transformation result from position vector of ZMP in each IP with roll rotation. \( P_{(H,T,L),zmp,(x,y)}^T \) is the position vector from PID controller output. \( P_{(H,T,L),real,(x,y)} \) is the
position vector in real time condition. $\theta_{(H,T,L),CoM,(P,R)}$ is the angular position in real time condition from FS.

The general equation of PID controller for the 3 serial SISO push recovery strategy (closed-loop) is shown in Equation 17 and Equation 18 as follows.

$$e_{(H,T,L),(x,y)}(t) = \left( P_{(H,T,L),xmp,(x,y)}(t) - P_{(H,T,L),Real,(x,y)}(t) \right)$$ \hspace{1cm} (17)

$$U_{(H,T,L),(x,y)}(t) = K_p,(H,T,L),(x,y) \left( e_{(H,T,L),(x,y)}(t) \right) + K_i,(H,T,L),(x,y) \int_0^t \left( e_{(H,T,L),(x,y)}(\tau) \right) d\tau \hspace{1cm} (18)$$

The value of $K_p,(H,T,L),(x,y)$, $K_i,(H,T,L),(x,y)$, and $K_d,(H,T,L),(x,y)$ in the PID controller will be tuned by using Ziegler-Nichols tuning methods. This method is used as one of the way to tune the PID controller. This method is work based on step response requirement of the system (figure 8) [22]. The tuning formulas can be seen in table 2.

**Figure 8.** S-shaped step input response of the plants.

**Table 2.** Ziegler-Nichols tuning rule based on step response of plants.

| Type of Controller | $K_p(n)$       | $K_i(n)$       | $K_d(n)$       |
|-------------------|----------------|----------------|----------------|
| P                 | $\gamma_{ZL}/\beta_{ZL}$ | $\infty$      | 0              |
| PI                | $0.9\gamma_{ZL}/\beta_{ZL}$ | $\beta_{ZL}/0.3$ | 0              |
| PID               | $1.2\gamma_{ZL}/\beta_{ZL}$ | $2\beta_{ZL}$ | $0.5\beta_{ZL}$ |

**6. Experiment Result**

The experiment of push recovery in this section is using pendulum model to generate an external force. The robot is receiving the external force from the backward direction (X-axis). Before the experiment, the PID controller (closed-loop) is tuned by using Ziegler-Nichols tuning methods and the result of this tune can be seen in table 3. The pendulum (force generator) is drawn to certain angles so the pendulum will swing and causing an external force against the robot’s body. The pendulum is swinging directly into trunk part of the robot body. Because in this experiment is only focus on the implementation of push recovery strategy during external force directly into the trunk with the only
forward direction (X-axis). The pendulum has weight about 2.33 Kg and length about 115 cm as table 4 as follows.

**Table 3.** Tuned Constanta of PID controller using Ziegler-Nichols tuning methods.

| Part | \( K_p (\text{Pitch}) \) | \( K_i (\text{Pitch}) \) | \( K_d (\text{Pitch}) \) | \( K_p (\text{Roll}) \) | \( K_i (\text{Roll}) \) | \( K_d (\text{Roll}) \) |
|------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Head | 2.4             | 0.2             | 0.05            | 1.5             | 0.16            | 0.04            |
| Trunk| 1.5             | 0.4             | 0.1             | 1.8             | 0.2             | 0.05            |
| Legs | 1.92            | 0.5             | 0.125           | 2.0             | 0.3             | 0.075           |

**Table 4.** Specification of Pendulum (External Force Generator).

| Part | Description |
|------|-------------|
| Length | 115 cm |
| Distance | 56 cm |
| Weight | 2.23 Kg |

By using this tuned constanta, the PID controller is ready to use in the push recovery control strategy. The experiment is comparing the open-loop push recovery control strategy and closed-loop (3 serial SISO) push recovery control strategy. The experiment is starting with a small certain angle in the pendulum to generate a small external force and the result can be seen in table 5.

**Table 5.** Implementation experiment result of push recovery strategy in T-FLoW humanoid robot.

| Pendulum Angle (Force Generator) (Degree) | Without Control | With Control |
|------------------------------------------|-----------------|--------------|
| 5                                        | Success         | Success      |
| 10                                       | Success         | Success      |
| 15                                       | Not Success     | Success      |
| 20                                       | Not Success     | Success      |
| 25                                       | Not Success     | Success      |
| 30                                       | Not Success     | Success      |
| 35                                       | Not Success     | Not Success  |

From table 5 can be seen the experiment result of push recovery strategy implementation comparison between open-loop control system and closed-loop control system. When the robot doing push recovery challenge using open-loop control system, the percentage of successful withstand is about 28.57% and robot falls is about 71.43%. When the robot doing push recovery challenge using closed-loop control system, the percentage of successful withstand is about 85.71% and robot falls is just about 14.29%. From the experiment also known the maximum value of external force that can be handled by push recovery strategy is about 30 degrees of pendulum angle. In figure 9 shows the push recovery strategy at a maximum angle about 30 degrees of pendulum angle and the comparison in each IP can be seen in figure 10, figure 11, and figure 12. From the position vector comparison shows when using closed-loop control system, the robot withstands and keeps standing (red line) and when using open-loop control system, the robot is fall (blue line).
Figure 9. Implementation sample of push recovery strategy from table 5 during maximum external force (30 degrees of pendulum angle). In this figure shows, the robot control system reached the critical condition because of the position vector of ZMP almost outside SP.

In figure 10, figure 11, and figure 12, there are Fall area and Safe area. Fall area is area when the robot is impossible to maintain the balance. When the robot reaches this condition even in short time, the robot will fall. The safe area is area when the robot is still possible to balancing the body. When the robot reaches this condition, the robot has a chance to maintain the body balance to avoid fall condition.

The Inverted Pendulum 1 is shown in figure 10. In data without PID controller (open-loop), the standard deviation (SD) of data is about 14.12 and the maximal minimal angle of data is about (46 ~ -1) degree. In data with PID controller (closed-loop), the SD of data is about 5.163 and the maximal minimal angle of data is about (29 ~ -18) degree.

Figure 10. Position vector comparison of ZMP during maximum external force in the first IP (Head).
The Inverted Pendulum 2 is shown in figure 11. In data without PID controller (open-loop), the standard deviation (SD) of data is about 15 and the maximal minimal angle of data is about (50 ~ 1) degree. In data with PID controller (closed-loop), the SD of data is about 9.738 and the maximal minimal angle of data is about (33 ~ -10) degree.

![Figure 11](image1)

*Figure 11. Position vector comparison of ZMP during maximum external force in the second IP (Trunk).*

The Inverted Pendulum 3 is shown in figure 12. In data without PID controller (open-loop), the standard deviation (SD) of data is about 15.59 and the maximal minimal angle of data is about (51 ~ 1) degree. In data with PID controller (closed-loop), the SD of data is about 7.398 and the maximal minimal angle of data is about (25 ~ -7) degree.

![Figure 12](image2)

*Figure 12. Position vector comparison of ZMP during maximum external force in the third IP (Legs).*

7. Conclusion and Discussion

The main result of the experiment when receiving maximum external force at 30 degrees of pendulum angle is a robot with open-loop control system has been falling and a robot with closed-loop control system has been successfully (withstanding) from external force and keeps standing. The difference in percentage of successful withstand is about 85.71% when using push recovery control strategy (closed-loop control system) and about 28.57% without using push recovery control strategy (open-loop control system).
But a new problem is appeared, that is, push recovery control strategy (closed-loop control system) cannot handle and damp the external force up to 30 degrees of pendulum angle. It is because the position vector of ZMP in the critical condition (the position vector of ZMP almost outside SP). With this problem, the future research will be focused on a strategy deals with the walking stepoff when reaching the critical condition and try to use another controller such as FUZZY, Neural Network, and etc to improve and compare the differences result from the present research.

References
[1] Technical Committee of RoboCup Humanoid League, 2017, Robocup Soccer Humanoid League Laws of the Game 2016/2017, pp. 58–63
[2] Luca B and Alberto L.D, 2008, Nonparametric decoupling of MIMO systems, Proc. IEEE International Conference on Computer-Aided Control Systems, CACSD 2008, pp. 1073–1078
[3] B. A. Ogunsaine, W. H. Ray, 1979, Multivariable controller design for linear systems having multiple time delays, AIChE Journal, Vol. 25, No. 6, pp. 1043–1057
[4] K.G. Ellohany, 1997, Real time stabilization of a triple link inverted pendulum using single control input, IEEE Proc. Control Theory and Application, Vol. 144, No. 5, pp 498–504
[5] V.A. Tsachouri & G.A. Medrano-Cerda, 1999, Discrete-time H∞ control of a triple inverted pendulum with single control input. IEEE Proc. Control Theory and Application, Vol. 146, No. 6, pp 567–577
[6] R. Dimas Pristovani, W. M. Rindo, B. Eko H., K. H. Achmad S., and Dadet P., 2016, Basic walking trajectory analysis in FLoW ROBOT, Proc. 2016 Int. Electronics Symposium (IES), pp 333–338
[7] K. Nuril E., D. Raden S., Dadet P., 2017, “FLoW” bipedal robot: squat and walk motions, Int. J. of Advanced Science Letters, Vol. 23, Issue 5, pp. 3838-3842
[8] M. Vukobratovic, A. A. Frank, and D. Juricic, 1970, On the stability of biped locomotion, in: IEEE Transactions on Biomedical Engineering, pp. 25–36
[9] Benjamin J.S. and Christopher G.A., 2010, Dynamic balance force control for compliant humanoid robots. 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp 1248–1255.
[10] P. Derry, B. Eko H., A. Fernando, 2015, Movement control of two wheels balancing robot using cascaded PID controller. 2015 International Electronics Symposium (IES), pp 100–105
[11] Akshub P., Apoorv P., and Somya G., 2016, Push recovery for humanoid robot in dynamic environment and classifying the data using K-Mean, Int. J. of Interactive Multimedia and Art, Vol. 4, No. 2, pp. 29–34
[12] Y.F. Zheng, 1989, Acceleration compensation for biped robots to reject external disturbances, In: IEEE Transactions on Systems, Man and Cybernetics, Vol. 19, No. 1, pp. 74–84
[13] Y. Wei, B. Gang, W. Zuwen, Balance recovery for humanoid robot in the presence of unknown external push, In: ICMA 2009 Int. Conf. on Mechatronics and Automation, pp. 1928–1933
[14] Benjamin J. Stephens, 2007, Humanoid Push Recovery, In Proc. IEEE-RAS Int. Conf. on Humanoid Robots (Humanoids), pp. 589 – 595
[15] Chao Li, Rong XIONG, Qiu-guo ZHU, Jun WU, Ya-liang WANG, Yi-ming HUANG, 2015, Push Recovery for The Standing Under-Actuated Bipedal Robot Using the Hip Strategy, In Proc. Int. Journal: Frontiers of Information Technology & Electronic Engineering, pp. 579 – 593
[16] Seung-Joon Yi, Byoung-Tak Zhang, Dennis Hong, Daniel D. Lee, 2012, Active Stabilization of a Humanoid Robot for Impact Motions with Unknown Reaction Forces, In Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and System, pp. 4034 – 4039
[17] Sang-Ho Hyon, Joshua G. Hale, and Gordon Cheng, 2007, Full-Body Compliant Human–Humanoid Interaction: Balancing in the Presence of Unknown External Forces, In Proc. Int. Journal: IEEE Transaction on Robotics, Vol. 23, No. 5, pp. 884 – 898
[18] Awais Yasin, Qiang Huang, Qian Xu, M. Saad Sultan, 2012, Humanoid Robot Push Recovery through Foot Placement, In *Proc. IEEE Int. Conf. on Mechatronics and Automation*, pp. 59 – 63.

[19] Christian Ott, Maximo A. Roa, Gerd Hirzinger, 2011, Posture and Balance Control for Biped Robots based on Contact Force Optimization, In *Proc. IEEE-RAS Int. Conf. on Humanoid Robots (Humanoids)*, pp. 26 – 33.

[20] Albertus Hendrawan A, Chee-Meng Chew, Weiwei Huang, Van Huan D, 2010, Humanoid Robot Push Recovery through Walking Phase Modification, In *Proc. IEEE Int. Conf. on Robotics Automation and Mechatronics (RAM)*, pp. 569 – 574.

[21] Kenji Kaneko, Fumio Kanehiro, Mitsuhiro Morisawa, Eiichi Yoshida, 2012, Disturbance Observer that Estimates External Force acting on Humanoid Robots, In *12th IEEE Int. Workshop on Advance Motion Control (AMC)*

[22] Ziegler, J.G and Nichols, N. B, 1942, Optimum setting for automatic controllers, In *Proc. IEEE Transactions of the ASME*. Vol. 64, pp. 759–768

**Acknowledgments**
Gratefulness to Ministry of Research, Technology and Higher Education of the Republic of Indonesia for financial support and EEPIS Robotics Research Center (ER2C) laboratory.