# A Steering Stability Control for A Three-Wheeled Autonomus Electric Vehicle

Hilman Lajuardhie
*Departement of Electrical Engineering*
*UIN Sunan Gunung Djati Bandung*
Bandung, Indonesia
hilmanlajuardhie@gmail.com

Arief Suryadi Satyawan
*Research Center for Telecommunication The National Research and Innovation Agency, Department of Electrical Engineering Nurtanio University*
Bandung, Indonesia
arie021@brin.go.id

Adam Faroqi
*Departement of Electrical Engineering*
*UIN Sunan Gunung Djati Bandung*
Bandung, Indonesia
AdamFaroqi@uinsgd.ac.id

Fauzan Ali Rasyid.
*Department of Constitutional Law*
*UIN Sunan Gunung Djati Bandung*
Bandung, Indonesia
fauzan.ali.rasyid@uinsgd.ac.id

2022 8th International Conference on Wireless and Telematics (ICWT) | 978-1-6654-5122-2/22/$31.00 ©2022 IEEE | DOI: 10.1109/ICWT55831.2022.9935468

***Abstract*— One of the essential systems in operating a vehicle is a steering system. This paper tells about the design of a steering system for an electric vehicle that runs with three wheels. The steering system employs a Brushless Direct Current (BLDC) motor coupled with consecutively connected gears. Establishing the steering system to perform precise directions while the motor is driving is critical; therefore, an automatic control mechanism must be developed to manage the direction stability. The PID algorithm is applied to perform the steering stability control in this research with the help of the controlling tuning method performed by the Ziegler-Nichols II. The results showed that this method can achieve a precise position on the steering wheel deflection. Furthermore, this method is promising to support autonomous capability in the vehicle.**

***Keywords—Control, PID, Steering, Stability, Ziegler-Nichols.***

## I. Introduction

The development of electric vehicles has grown exponentially in recent years due to the rapid growth of batteries and electric motors that are more powerful and efficient. Electric cars have several advantages, including no gas emissions, better torque, higher energy efficiency, etc. Electric vehicles are developed mainly by incorporating four wheels or three wheels configurations. Unlike conventional cars with four wheels, vehicles with three wheels configurations have more extreme manoeuvrability characteristics. Furthermore, the three wheels designs have minor vehicle static stability, while production and maintenance costs are minimal. The disadvantage of the three-wheeled vehicles is the lack of stability compared to four-wheeled ones, especially during cornering manoeuvres.

Electric vehicles generally make use of an electric motor actuator, which usually runs by using an AC or DC motor. DC motors provide a simple and precise control method and have a long history of use in various industries. As well as being efficient, the DC motors exhibit high starting torque, which helps to prevent random and sudden load increasing. BLDC motors have become the most suitable replacement, and they can replace conventional DC motors because of the higher torque and speed [1], [2].

In this work, the developed vehicle is a three-wheeled electric vehicle that can be upgraded to have an autonomous capability. This car requires an automatic control to respond to set points given by a sensor so that the steering deflection can be changed appropriately [3]. To be able to do that, a PID control mechanism is incorporated as the basis for the steering control, and the Ziegler-Nichols II method is nominated. Using the PID's ZN II, the steering system can be operated autonomously by using the appropriate set point input given by the sensor signals. Furthermore, this method simplifies the implementation of the control mechanism since it can be applied directly to the system without previously simulating a control model [4].

## II. Theories

### *A. Three-wheeled vehicle*

The structure of the three-wheeled electric vehicle, which uses a tadpole rear steering type, can be seen in Fig. 1.

Fig. 1 Three-Wheeled Vehicle.

The structure of a three-wheeled electric vehicle is fascinating. The tadpole configuration and the rear-wheel steering on such a vehicle have more extreme manoeuvres because it has a relatively low balance compared to a four-wheeled car in a manoeuvrable state especialy at high speeds [5]. If a vehicle with a three-wheel configuration is driven at a low speed, the steering control response will be more stable, this is because the center of rotation for taspole vehicles is always one point on the front axle [6].

### B. Steering Control System

In this study, the steering mechanism of the three-wheeled electric vehicle employs a BLDC motor, a gear set, a rotary encoder, a microcontroller, and a rear wheel, as seen in Fig. 2.

Fig. 2 Steering Mechanism.

The mechanism of the steering system employs a BLDC motor as an actuator. This motor uses gears plugged into the electric motor shaft, which aims to provide mechanical advantages for the rotation of the electric motor to the steering wheel, which is in the form of the capability to regulate speed rotation and mechanical torque of the load received [7], [8]. The gear also aims to monitor the rotary encoder sensor to get position feedback from the rear wheel, which is also the steering wheel.

### C. PID

There are several kinds of actions In PID control, including proportional control actions, integral control actions, and derivative control actions. Each of these control actions has certain advantages, where the proportional control actions are capable of reducing steady-state errors, the integral control actions can accelerate system response, and the derivative control actions are able to mitigate overshot/undershot and steady-state error [4].

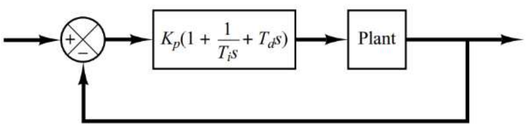


Fig. 3 PID Controller.

The diagram shown in Fig. 3 tells that the PID controller schematic can be expressed mathematically by

$$G(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{1}$$

Where $K_p$ is the proportional gain, $t_i$ is the integral time, $t_d$ is the derivative time, and s is the frequency domain. The PID mechanism is the sum of three control elements such as Proposal control ($K_p$), Integral control ($K_i$), and also Derivative control ($K_d$) [9].

### D. Ziegler-Nichols II Tuning Method

The gain value of $K_p$, $K_i$, and $K_d$ should be found to turn up the PID control. One of the methods of calculating those is Ziegler-Nichols II. In this method, adjustment to the PID can be made with a closed-loop scheme where the input reference is a step function. The controlling process in this method begins by looking for a constant oscillation state; hence the $K_{cr}$ and $P_{cr}$ parameters can be obtained, and finally, the $K_{cr}$ and $P_{cr}$ parameters can be produced [10]. The description shown in Fig. 4, with its parameters stated in Table 1, describes how the Ziegler-Nichols II method works.

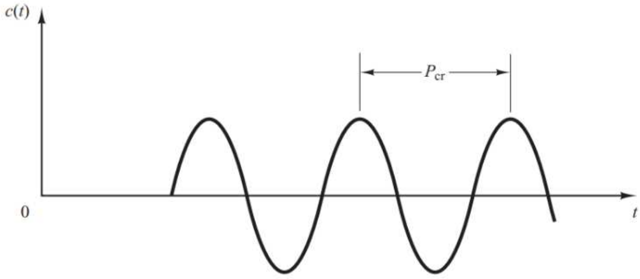


Fig. 4 Ziegler-Nichols II Response Analysis.

TABLE I ZIEGLER-NICHOLS II TABLE.

| Type of Controller | $K_p$ | $t_i$ | $t_d$ |
|---|---|---|---|
| P | $0.5K_{cr}$ | $\infty$ | 0 |
| PI | $0.45K_{cr}$ | $0.833P_{cr}$ | 0 |
| PID | $0.6K_{cr}$ | $0.5P_{cr}$ | $0.125P_{cr}$ |

After obtaining the $K_{cr}$ and $P_{cr}$ parameters, the PID gain values can be obtained with the help of the Ziegler-Nichols II table. This process can be done by substituting the $t_i$ and $t_d$ in the transfer function of the PID control itself. Performing the Ziegler-Nichols II tuning method will show that the control system can be tuned directly to the plant.

## III. DESIGN

A design with a robust analysis is needed to produce a stable vehicle steering system. To realize that, a preliminary analysis of the dynamics, a steering mechanism, a tuning method, and a control system design must be carried out; hence it can be used to produce a stable control system with the desired output value.

### A. Dynamic Analysis

By using dynamic analysis, the impact of the deflection of the rear wheel as a steering wheel on the total deflection of the vehicle and the effect of steering stability on three-wheeled vehicles can be known [1]. The dynamic diagram can be seen in Fig. 5.

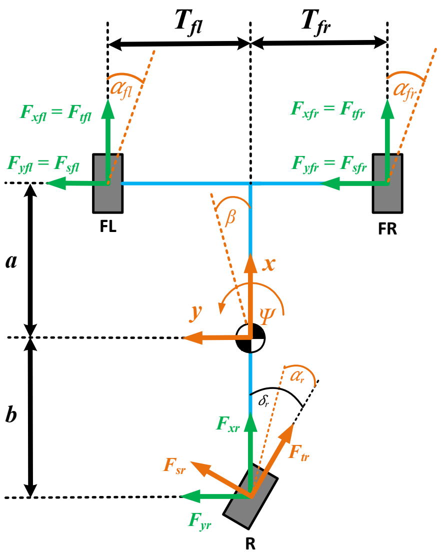


Fig. 5 Dynamic Diagram.

As can be seen that the deflection of the rear wheel has the opposite direction to the total deflection or yaw moment of the vehicle. This condition happened due to the rear wheel steering configuration. When the rear wheels deflect to the left, at the same time, the overall car deflects to the right. The rear steering configuration also causes the vehicle to have more extreme manoeuvres, especially when turning around. This situation is due to the tadpole configuration, which only has two wheels in front and one in the back.

## B. *Steering Mecanism*

The steering mechanism on a three-wheeled electric vehicle takes advantage of a BLDC motor which is coupled with a gear, and the gear is plugged into the rear wheel to perform a rear steering wheel. The gear is also applied to a rotary encoder so that the steering wheel's position can be read. This system can be seen in Fig. 6.

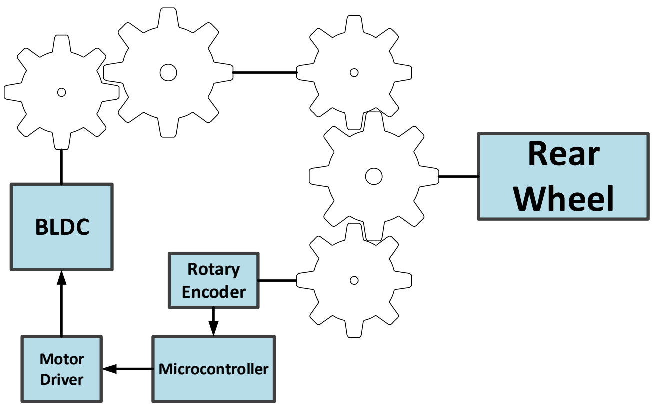


Fig. 6 Steering Mechanism Diagram.

The input gear of the motor will rotate at an angle due to mechanical torque. The output gear reacts calmly to the input gear, which is driven by the motor so that the output gear can rotate and produce torque [7]. If the input gear with radius $r_1$ and the number of teeth $N_1$ is given a mechanical torque $T_1$ then it rotates through an angle of $\theta_1$, output gear will rotate through $\theta_2$ and produce $T_2$ on output gear with radius $r_2$ and the number of teeth $N_2$. In this condition, if the moment of inertia and the damping are neglected, then the steering mechanism equation becomes

$$r_1\theta_1 = r_2\theta_2. \tag{2}$$

If radius of the gear equal to the number of gear teeth than the equation became

$$\frac{\theta_2}{\theta_1} = \frac{r_1}{r_2} = \frac{N_1}{N_2} \tag{3}$$

The equation shows that the ratio of the input angular displacement to the output gear will be inversely proportional to the ratio between the gear-ratio.

Suppose the input gear ratio is smaller than the output gear ratio. In that case, the mechanical torque generated or distributed to the rear wheels is more considerable than the actuator. This condition happened because the gear ratio on the motor actuator is smaller than the output gear on the rear wheels. Hence, the rotational speed of the rear wheel is slower than the rotational speed of the actuator. Furthermore, the direction of the rear wheel is opposite to the motor's gearbox rotational direction.

## C. *Control System Design*

By making use of the analysis of the vehicle dynamics and the steering mechanism on a three-wheeled autonomous electric vehicle, the design of a control system, which employs PID and the Ziegler-Nichols II tuning method, can be developed appropriately. This control system design is shown in Fig. 7.

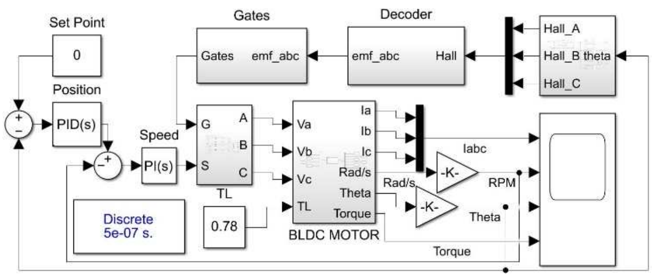


Fig. 7 Control System Design.

As can be seen on the fig. 7 that there are two types of controllers in the control system design named the PI controller for the speed of the BLDC motor and the PID controller for the stability of the rear wheel position. This condition is because to control the position appropriately; it is necessary to stabilize the motor speed. On the control system design, there is also a speed conversion from rad/s, which is the motor output in rpm, and it is fed back to the controller where the reference uses rpm units. There is also a gear ratio conversion that reads the position of the rear wheel deflection instead of the motor's rotor position.

Negative gain is not applied after the set point for the position purpose. This condition is because the readable position is the deflection position of the rear wheel only not the total rotation of the vehicle, and it is the steering wheel, where the dynamics of the rear wheel deflection has a rotating direction, which is inversely proportional to the deflection or rotation direction of the BLDC motor as the actuator. Therefore, the negative gain is needed to get the desired position.

# IV. IMPLEMENTATION AND ANALYSIS

Implementing the control system on the vehicle using PID with the Ziegler-Nichols II method can be done directly without using simulation or mathematical modelling. This method can be realized by analysing the system without control, application of PID with the Ziegler-Nichols II method, and analysing of system response after final tuning.

## A. Response Systems without Controller

The steering response system can be seen from the deflection of the output gear towards the rear wheel, which is recorded by the microcontroller through the rotary encoder. A steering system without a controller can be implemented by determining the speed of the actuator. In this case, the BLDC motor whose the response system without a controller can be seen in Fig. 8.

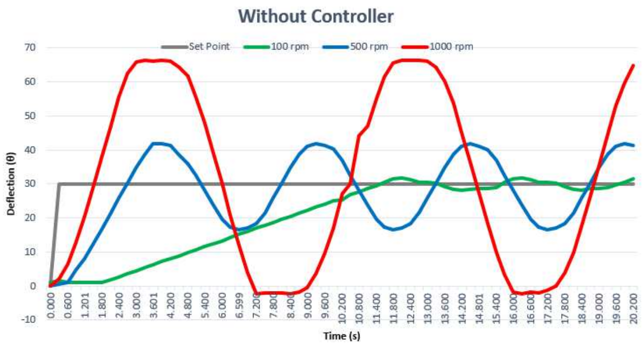


Fig. 8 Without Controller.

TABLE II WITHOUT CONTROLLER.

| *Speed (rpm)* | *Overshoot (%)* | *Rise Time (s)* | *Delay Time (s)* | *Settling Time (s)* | *Steady-state Error* |
|---|---|---|---|---|---|
| 100 | 5.7 | 11.7 | 5.85 | - | - |
| 500 | 39.23 | 2.7 | 1.35 | - | - |
| 1000 | 121.33 | 1.8 | 0.9 | - | - |

The steering system, in general, has a very uncontrollable response. It can be seen in Table 2 that the response value with a motor speed of 100 rpm has a very long response, even though it has a low steady-state error. In contrast, the speed of 1000 rpm has a fast response but has an extensive state of overshoot. From the same table, it can also be seen that the responses with a low or a high speed do not all find the settled state or the desired state. This condition proves that a usable controller has to be capable of making the steering system have a fast response and a small steady-state error. This condition can be realized by applying the classical control, namely the PID controller using the Ziegler-Nichols II tuning method.

## B. Ziegler-Nichols II Tuning Methode

The PID control with the Ziegler-Nichols II tuning method can be designed by looking for stable oscillation conditions so that the $K_{cr}$ and $P_{cr}$ parameters can be obtained to find the PID gain ($K_p$, $K_i$, and $K_d$). This process can use the Ziegler-Nichols II table so that at the same time, the $K_p$, the $t_i$, and also the $t_d$ can be collected. From then on, by using the PID transfer function (equation 1), the values of $t_i$ and $t_d$ that have been obtained from the calculations in the Ziegler-Nichols II table can be substituted for the PID transfer function to get the gain values of $K_p$, $K_i$, and $K_d$. The PID gain can be found by the equation

$$K_p = 0.6K_{cr} \tag{4}$$

$$K_i = \frac{Kp}{ti} \tag{5}$$

$$K_d = t_d(K_p) \tag{6}$$

Calculating those Ziegler-Nichols II tuning modes will produce the PID gain obtained with coefficients $K_p$ = 34.8, $K_i$ = 8.4, and $K_d$ = 29.9. The response of the Ziegler-Nichols II tuning method can be seen in Fig. 9 and Table 3.

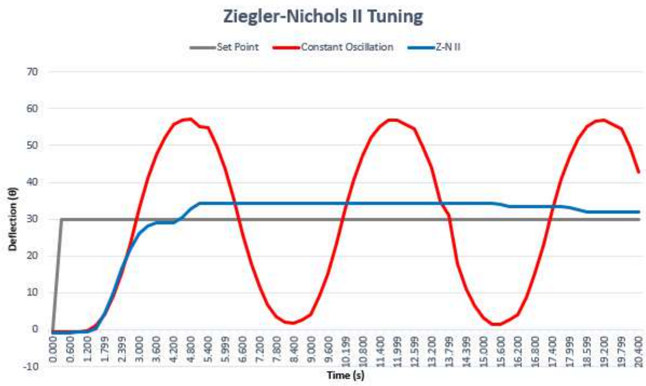


Fig. 9 Ziegler-Nichols II Tuning.

TABLE III ZIEGLER-NICHOLS II TUNING.

| *Deflection (θ)* | *Overshoot (%)* | *Rise Time (s)* | *Delay Time (s)* | *Settling Time (s)* | *Steady-state Error* |
|---|---|---|---|---|---|
| 30 | 14.5 | 4.5 | 2.25 | 18.59 | 1.95 |

From Fig. 9 and Table 3, it can be analysed that using the Ziegler-Nichols II tuning method, the system response from the vehicle steering can reach the desired state despite a very long response, which is indicated by the settling time of 18.59 seconds. This result is awful, particularly when it is used on the vehicle's steering system. The settling time is the time required for a system to reach a stable state or an endpoint in the reaction of a system, and it should not be larger than 1 degree to preserve a precise position on steering wheel deflection.

The steering stability control system requires a faster response with a smaller tolerance; therefore, a re-tuning process is needed to get that need.

## C. Respon System with Controller

After getting the tuning reference generated by the calculation on the table of the Ziegler-Nichols II method, a little retuning is needed based on the reference obtained. This process is necessary due to the slow response and the large steady-state error, which does not support the vehicle steering system.

By considering specifications of the desired system response, which is influenced by the dynamic characteristics of the vehicle, the analysis of the steering mechanism, also the tuning reference from the calculations and experiments of the Ziegler-Nichols II method, the gain values of $K_p$ = 34, $K_i$ = 0.2, and $K_d$ = 9.92 for the PID gain coefficient can be obtained.

The response of the steering stability control system on the three-wheeled vehicles can be seen in Fig. 10 and Table 4.

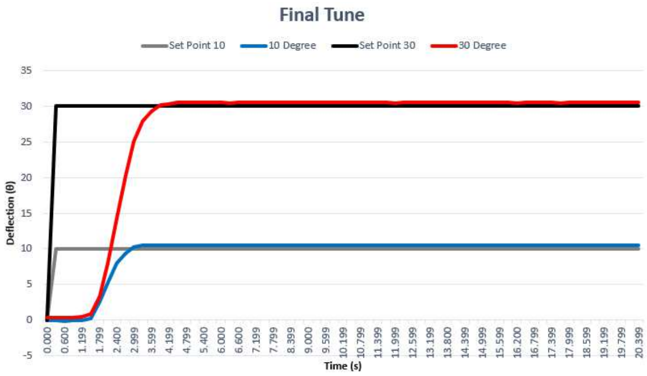


Fig. 10 Final Tuning.

TABLE IV FINAL TUNING.

| *Deflection* *(θ)* | *Overshoot* *(%)* | *Rise Time* *(s)* | *Delay Time* *(s)* | *Settling Time* *(s)* | *Steady-state Error* |
|---|---|---|---|---|---|
| 10 | 0 | 2.99 | 1.49 | 3.29 | 0.48 |
| 30 | 0 | 3.89 | 1.94 | 4.49 | 0.54 |

From Fig. 10, it can be seen that the system response is proportional enough for the steering control system of the three-wheeled electric vehicle, where the response results have a reasonably robust characteristic, and it's not too aggressive as well, in accordance with the dynamics of a three-wheeled vehicle that has more extreme manoeuvres, but still has a responsive response and has excellent precision as it will function as vehicle steering control.

The final response system can be seen in table 4. It can be analysed by applying a retuning process from the calculation results incorporating the Ziegler-Nichols II table. The results of the final tuning response have faster and more precise. It can be seen that the rise time is 1.51 seconds faster when a deflection of 10 degrees and 1.11 seconds faster when a deflection of 30 degrees. The overshoot has been removed, as can be seen in Fig. 10. The response to a deflection of 10 degrees and 30 degrees has prevented the system from overshooting. The setting time results also have a very rapid change compared to the tuning reference, where the settling time is 15 seconds faster than the response generated by the tuning reference.

## V. CONCLUSION

The three-wheeled vehicle steering system basically has very uncontrollable characteristics. It is unsuitable to be used as a vehicle steering system because it has a lengthy response, higher overshoot, or makes it hard to reach the desired point. This condition can be overcome by applying a PID control with the Ziegler-Nichols II method. This method performs tunings two times. The first tuning comes from the Ziegler-Nichols II table and the calculation of the PID transfer function, which produces the value of $K_p = 34.8$, $K_i = 8.4$, and $K_d = 29.9$. While the second tuning is collected by making adjustments to get the desired control so that the PID gain indicates the value of $K_p = 34$, $K_i = 0.2$, and $K_d = 9.92$. These numbers act as control gains, which will be applied to the steering mechanism of the three-wheeled electric vehicle.

Applying the PID control system with the Ziegler-Nichols II tuning method can make the system have a control system response. It is helpful to control steering stability on the three-wheel electric vehicle. In other words, the automatic control is very suitable for the operation of the vehicle steering systems; therefore, it can support the autonomous capability of the vehicle.

## REFERENCES

[1] G. Vasiljevic, Z. Vrhovski, and S. Bogdan, "Dynamic Modeling and Simulation of a Three-wheeled Electric Car," in *International Electric Vehicle Conference (2012)*, 2012. doi: 10.1109/IEVC.2012.6183186.

[2] Y. Li, Q. Cao, and F. Liu, "Research on Fuzzy PID Control of Electronically Controlled Hydraulic Power Steering System for Unmanned Agricultural Vehicle," in *International Conference on High Performance Big Data and Intelligent Systems (HPBD & IS)*, 2019, pp. 9–11. doi: 10.1109/HPBDIS.2019.8735485.

[3] M. S. Saidonr, H. Desa, and M. N. Rudzuan, "A differential steering control with proportional controller for an autonomous mobile robot," in *7th International Colloquium on Signal Processing and Its Applications*, 2011, pp. 90–94. doi: 10.1109/CSPA.2011.5759849.

[4] N. Nabilah, M. N. Thamrin, and N. A. Razak, "Comparison Between Ziegler-Nichols and AMIGOTuning Techniques in Automated Steering Control System for Autonomous Vehicle," in *International Conference on Automatic Control and Intelligent Systems (I2CACIS)*, 2020. doi: 10.1109/I2CACIS49202.2020.9140089.

[5] Y. Liu, B. Xiao, Z. Jiang, and Y. He, "Optimal Control of Three-Wheel Steering Forklift with Steer-by-Wire," in *36th Chinese Control Conference (CCC)*, 2017, pp. 4719–4723. doi: 10.23919/ChiCC.2017.8028097.

[6] R. N. Jazar, *Vehicle Dynamics: Theory and Application*. Manhattan, 2008.

[7] M. Azzumar, "Pemodelan dan Desain Kendali Sistem Aktuator Kendali Sirip Berbasis Brushless DC Motor, (in bahasa)" Universitas Indonesia, Depok, 2012.

[8] Y. Nianjiong and L. Qifeng, "Design and Simulation for Steer-by-Wire System Based on Fuzzy-PID," in *7th International Conference on Intelligent Human-Machine Systems and Cybernetics*, Nov. 2015, vol. 1, pp. 291–294. doi: 10.1109/IHMSC.2015.43.

[9] Katsuhiko. Ogata, *Modern Control Engineering*, vol. 5. Prentice-Hall, 2010.

[10] E. C. Wijaya, I. Setiawan, and Wahyudi, "Auto Tuning PID Berbasis Metode Osilasi Ziegler-Nichols Menggunakan Mikrokontroler AT89S52 pada Pengendalian Suhu, (in bahasa)" Universitas Diponogoro, Semarang, 2011.