Table of contents

Volume 508

2019

Tarumanagara International Conference on the Applications of Technology and Engineering 22–23 November 2018, Jakarta, Indonesia

Accepted papers received: 08 March 2019
Published online: 03 May 2019

Open all abstracts

Preface

Papers

Civil and Enviromental Engineering

Potential study of ground water lembah keramat Tidore Island

Wati Asriningsih Pranoto and Tri Suyono

+ Open abstract   🗏 View article   📄 PDF

    012002

Mode choice analysis between LRT and car route Kebayoran Lama-Kelapa Gading

Najid

+ Open abstract   🗏 View article   📄 PDF

    012003

Critical Index Determination Method on Visual Assessment of Concrete Damage for Buildings

Henny Wiyanto, David Lie and James Kurniawan

+ Open abstract   🗏 View article   📄 PDF

    012004

Effect of Axle and Tire Configurations on Flexible Pavement Response

A N Tajudin and R Priyatna

+ Open abstract   🗏 View article   📄 PDF

    012005

Concept of sediment filtration intake design for raw water drinking water

Muchlis, Wati Asriningsih Pranoto and Tri Suyono

+ Open abstract   🗏 View article   📄 PDF

    012006

Effect of steel fiber on the shear strength of reactive powder concrete

Daniel Christianto, Tavio and Dennis Kurniadi

+ Open abstract   🗏 View article   📄 PDF

V Kurniawan

+ Open abstract   🗏 View article   📄 PDF

012013

The use of an online survey to speed up the data collection process

L S Putranto

+ Open abstract   🗏 View article   📄 PDF

012014

Simplified activities model for earned duration calculation

Basuki Anondho, Yusuf Latief, Khrisna Mochtar and Joshua Aditya

+ Open abstract   🗏 View article   📄 PDF

012015

Dynamic response of ground floor slab due to friedlander local load

Wilianto Aulia and Sofia W. Alisjahbana

+ Open abstract   🗏 View article   📄 PDF

012016

Cipularang toll road safety audit of traffic signs and road markings

Ni Luh Putu Shinta, M.I. Dewi Linggasari, Hendy Limawan and Antonius

+ Open abstract   🗏 View article   📄 PDF

012017

Dynamic deflection of concrete plate in semi-rigid supports and various damping condition

Yenny Untari Liucius and Sofia W. Alisjahbana

+ Open abstract   🗏 View article   📄 PDF

+ Open abstract   View article   PDF

012024

Relation between Transit Oriented Development (TOD) and the effect of electromagnetic field with fengshui on residential planning

S W Teh, F Lianto and R Trisno

+ Open abstract   View article   PDF

012026

Reconstructing the past: *from landform bath to spa-scraper of Taman Sari*

C Thedyardi and D Husin

+ Open abstract   View article   PDF

012027

Redesigning the isolation room for schizophrenia patients after a partial remission stage

Margaretha Sandi, Theresia Budi Jayanti, Rio Sanjaya and Kevin Tobias

+ Open abstract   View article   PDF

012028

Re-designing facade of kadin tower building (application of retrofit programme with OTTV)

Kisy Riniardi, Naniek Widayati Priyomarsono and James Rilatupa

+ Open abstract   View article   PDF

012029

Street network, transportation, and transit oriented development

Doddy Yuono

+ Open abstract   View article   PDF

012030

Planning of urban slum settlement in adaptation to landslide disaster

Liem Nadya Valencia, Suryono Herlambang and Liong Ju Tjung

+ Open abstract   View article   PDF

012031

Reference for contextual design

Franky Liauw

+ Open abstract   View article   PDF

012032

Effectiveness and efficiency of kitchen space reviewed from the kitchen triangle concept in small flats case study 'Rusunawa' Manis Jaya, Tangerang city, Banten

Ferdinand, R Trisno, S Gunanata, N Widayati, F Lianto and MB Susetyarto

+ Open abstract   View article   PDF

012033

The Development plan of 'Rusun' integrated modern market (case study: Grogol Market)

Muthiara Khairunnisa and Liong Ju Tjung

+ Open abstract   View article   PDF

012034

Comparison of PERT and M-PERT scheduling for a construction project in Malang, Indonesia

Joshua Reinaldo Handoko and Onnyxiforus Gondokusumo

+ Open abstract   View article   PDF

012035

Hydraulic analisys of drinking water pipeline inter island

Tri Suyono, Wati Asriningsih Pranoto and Agustinus Purna Irawan

---

OPEN ACCESS   012036

Children Friendly Environment in City Settlement: Study case : 'Kampung Luar Batang', North Jakarta

Mariana, T Fatimah, R Trisno, S Gunanta, M Bambang, N Widayati and F Lianto

---

OPEN ACCESS   012037

Organizational culture influence on implementation of knowledge management and quality management system for improving Indonesian construction companies' performances

Chairul Mubin and Yusuf Latief

OPEN ACCESS   012038

The long-term effects of nano-silica on concrete

Jonbi, P H Simatupang, A Andreas and A Nugraha

OPEN ACCESS   012039

The modeling of dwelling time of buses at bus stop

Alfa Narendra, Siti Malkhamah and Bertha Maya Sopha

OPEN ACCESS   012040

Identification of recharge area in Bengawan Solo Indonesia catchment areas based on Geographic Information System

Nindyo Cahyo Kresnanto and Edy Sriyono

Yurim Hatamaiya Setyorini and Yusuf Latief

+ Open abstract　　　📄 View article　　　📄 PDF

　　　012047

Recent study on the effect of blast loading on composite structures

Gunaryo, Bambang K. Hadi, Sigit P. Santoso and Yayat Ruyat

+ Open abstract　　　📄 View article　　　📄 PDF

　　　012048

Effect of recycled materials on marshall performance of hot asphalt mixture (HMA – RAP)

R T Bethary, B S Subagio, H Rahman and N Suaryana

+ Open abstract　　　📄 View article　　　📄 PDF

　　　012049

Implementation of standardized wbs (work breakdown structure) for time and cost performance. (study case: building project PT. X, Kuala Tanjung, Sumatera Utara)

Ayu Herzanita

+ Open abstract　　　📄 View article　　　📄 PDF

　　　012050

Design of Educational Therapic Facility for Children with Cerebral Palsy and Other Movement Disabilities (Case Study: Sayap Ibu Foundation, Bintaro)

Margaretha Sandi, Rio Sanjaya, Maria Veronica Gandha and Dewi Ratnaningrum

+ Open abstract　　　📄 View article　　　📄 PDF

　　　012051

Development of Mount Masigit area with geopark concept

Brenda Charisma Giovanni, Priyendiswara AB and Parino Rahardjo

+ Open abstract   View article   PDF

012063

Analytical model of retrofitted reinforced concrete beam column joints after experiencing severe damage from earthquake load simulation using SAP2000

N Gosal, I Imran and M Riyansyah

+ Open abstract   View article   PDF

012064

Friction stir welding of aluminium alloy 6061-t651

Richard A M Napitupulu, Sutan L M H Simanjuntak, Charles Manurung, Chilinton Hutabarat, S Sitompul and J N Aoh

+ Open abstract   View article   PDF

012065

Numerical simulation of styrofoam and rockwool heat transfer flat-plate type solar collector

Parulian Siagian, Richard Napitupulu, Sibuk Ginting, Miduk Tampubolon and Soeprapto Manurung

+ Open abstract   View article   PDF

012066

The behavior of various thin-walled aluminum prisms subjected by axial impact loading in relation to the energy absorption abilities

Witono Hardi

+ Open abstract   View article   PDF

012067

Eulerian multi-fluid simulation of biomass gasification in circulating fluidized beds: effects of equivalence ratio

H Wahyudi, I Rosyadi and M P Pinem

+ Open abstract   View article   PDF

012068

Analysis of near wake recovery scale model vawt hybrid wind turbin in wind tunnel

Erwin Erwin, Tresna Priana Soemardi, Adi Surjosatyo, Yulianto Sulistyo Nugroho, Kurnia Nugraha, Ratih Diah Andayani and Ismail

+ Open abstract   ▤ View article   🅿 PDF

012069

Multiple knapsack problem for racking selection model

Danan Anbiyaa, Erlangga Bayu Setyawan and Humiras Hardi Purba

+ Open abstract   ▤ View article   🅿 PDF

012070

Comparison analysis of overlay thickness using the AASHTO 1993 method and the everseries program

Faisal Gerardo, Bambang Sugeng Subagio, Jongga Jihanny and Gusfina Try Andari

+ Open abstract   ▤ View article   🅿 PDF

012071

Effects of alkali and steaming on tensile strength of aren (*arenga pinnata*) fiber

S Darmanto, S Sugeng, Indartono and E J Sasono

+ Open abstract   ▤ View article   🅿 PDF

012072

Influence of reaction layer thickness on surface/submerged flame during porous media combustion of micro burner

Ayub Ahmed Janvekar, M. Z. Abdullah, Zainal Arifin Ahmad, Aizat Abas, A K Ismail, Mohammad Nishat Akhtar, Hafifi Hafiz Ishak and Mazlan Mohamed

+ Open abstract   ▤ View article   🅿 PDF

012073

Optimization of open gear design for dryer paper machine transmission system

Renaldo, Agustinus Purna Irawan and Agus Halim

+ Open abstract View article PDF

012074

The effect of copper content on mechanical properties of Al3Si-Al$_2$O$_3$/SiC hybrid composite

Dwi Rahmalina, Hendri Sukma, Novan Kamanda and M Luthfi Aldiyansyah

+ Open abstract View article PDF

Electrical Engineering

012075

Performance analysis at the off body environment in terms of impedance matching, return loss and VSWR for wearable antenna system on different materials

Joni Fat, Syah Alam and Indra Surjati

+ Open abstract View article PDF

012076

Real time face detection using haar-like feature method and local binary pattern method

D Junaidy, M Wulandari and H Tanudjaja

+ Open abstract View article PDF

012077

Lighting Simulation of Flat and Slightly Arched Type Tunnel Based on Pasar Rebo Tunnel Data

Endah Setyaningsih and Jeanny Pragantha

+ Open abstract View article PDF

012078

Implementation of improved 3D interpolation technique on HRIR models using PCA

Hugeng Hugeng and Irfan Naufal

+ Open abstract View article PDF

012079

Deployment of models of HRIRs using PCA in digital signal processing board

Hugeng Hugeng and Tommy Sutiawan

✛ Open abstract   🗏 View article   📄 PDF

012080

Safe zone analysis of lightning protection system in antenna using radome

Arif Hidayat, Dedi Irawadi, Alfin Hikmaturokhman and Andrianingsih

✛ Open abstract   🗏 View article   📄 PDF

012081

An econometric analysis of energy input in the agricultural sector and its impact on co_2 emissions: a case of Indonesia

Charles O.P. Marpaung

✛ Open abstract   🗏 View article   📄 PDF

012082

Proportional integral derivative DC motor speed control system for xy plane movements

Hadian Satria Utama, William Wijaya and Joni Fat

✛ Open abstract   🗏 View article   📄 PDF

Industrial Engineering

012083

Analysis of Mak Diesel Engine Services at Merawang Power Plant Using FMEA Method

Lina Gozali, Kenty Lieanda, Lilyana Jap and Frans J. Daywin

✛ Open abstract   🗏 View article   📄 PDF

Decision Support System (DSS) analysis in raw material warehouse using system dynamics model (case study: PT. Modera Furintraco Industri)

012084

Ahmad Manbas, Lilyana and Kevin Oktavian

+ Open abstract   📄 View article   📄 PDF

Analysis and improvement of working methods to increase productivity (case study: float glass collecting process)

012085

Marcella, I Wayan Sukania, Lamto Widodo and Siti Rohana Nasution

+ Open abstract   📄 View article   📄 PDF

Analysis of productivity improvement in hard disc spare parts production machines based on OEE, FMEA, and fuzzy value in Batam

012086

Zeny Fatimah Hunusalela, Surya Perdana and Ridwan Usman

+ Open abstract   📄 View article   📄 PDF

Minerals compositions in wood processing waste for geopolymer base ingredient

012087

J M Supit, A D U Raharjo, J V Morin and N P P Nugroho

+ Open abstract   📄 View article   📄 PDF

Internalization of the champion core values in work system design and ergonomics learning

012088

Heri Setiawan and Rinamurti

+ Open abstract   📄 View article   📄 PDF

Reducing tyre scrap blister under tread with PDCA approach: a case study in manufacturing industry

012089

Wendi Kurniawan, Fery Andrianto Susilo, Humiras Hardi Purba and Siti Aisyah

+ Open abstract   View article   PDF

012090

Determination of optimum time of replacement with age replacement model

N Sembiring, M M Tambunan and F I Siahaan

+ Open abstract   View article   PDF

012091

Supplier selection in rubber industry using analytic network process (ANP) and technique for order preference methods by similarity to ideal solution

Nurhayati Sembiring, Nazaruddin Matondang and Abdul Rozak Dalimunthe

+ Open abstract   View article   PDF

012092

Reducing non conformance quality of yarn using pareto principles and fishbone diagram in textile industry

Fajar Pitarsi Dharma, Zulfa Fitri Ikatrinasari, Humiras Hardi Purba and Winda Ayu

+ Open abstract   View article   PDF

012093

Determination of critical indicators in efforts to improve performance of indonesian chocolate smes with lean and agile approaches

Siti Aisyah and Humiras Hardi Purba

+ Open abstract   View article   PDF

012094

Integrated manufacturing system framework for sustainable maritime tourism

Y Prasetyawan, L Yuwana, A Yuniarto, A Tira, F R Kurniawan and I O K Wardani

+ Open abstract   View article   PDF

012101

Dynamic capability and disruptive innovation within perspectives of industry 4.0, research result and innovation on people's prosperity

Khristian Edy Nugroho Soebandrija

012102

Impact of upgrading iso 9001:2008 to ISO 9001:2015 on internal rejects in automotive company

Afriyuddin, Diky Herdiawan, Humiras Hardi Purba and Hasbullah

---

012103

Analysis of hospital performance measurement using performance prism method

Rusmin Nuryadin, Ahmad Mughni, Humiras Hardi Purba, Afriyuddin and Euis Nina Saparina Yuliani

---

012104

The knock down system of rattan furniture for global market

Eddy Supriyatna Marizar, Agustinus Purna Irawan and Jap Tji Beng

---

012105

New development fiber material : use DoE approach to determine the best formula for blended fiber silk (Samiya Cynthia Riccini and Semi-Natural Fiber)

Fajar Pitarsi Dharma, Hendi Dwi Hardiman, Zulfa Fitri Ikatrinasari and Humiras Hardi Purba

012106

Empirical research of enterprise resource planning system implementation in indonesia: a preliminary study

Wilson Kosasih, Lithrone L. Salomon, Carla O. Doaly, R. Ryandi and S. Liman

+ Open abstract   View article   PDF

012107

Decreasing of musculoskeletal complaints through redesigns handling arit and palu products

Wahyu Susihono, Ellysa Kusuma Laksanawati and Suryanawati

+ Open abstract   View article   PDF

012108

The ergonomics design of the military backpack for Indonesian national soldiers using virtual environment model

Erlinda Muslim, Boy Nurtjahyo Moch, Bagus Anugrah Ramadhan Muhammad Rasyad and Pito Ananda Risya

+ Open abstract   View article   PDF

012109

Ergonomic design of electric vehicle instrument panel: a study case on Universitas Indonesia's national electric car

Erlinda Muslim, Boy Nurtjahyo Moch, Reshinta A Lestari, Ghassani Shabrina and Rinda Ramardhiani

+ Open abstract   View article   PDF

012110

User interface evaluation of mobile application krl access using user experience approach

Erlinda Muslim, Reshinta A Lestari, Asa Ibnu Hazmy and Sitti Alvina

+ Open abstract   View article   PDF

012111

Batik Industry Wastewater Treatment Using Fito Remidiation of Water Hyacinth with Adsorbent consist of Organic Waste Bagasse, Rice Husks and Bamboo Charcoal

Koosdaryani, M. Masykuri, Edy Purwanto and Suranto

+ Open abstract   ▤ View article   🅿 PDF

012112

Decision support system to choose private higher education based on marketing mix model criteria in Indonesia

Ragil Pardiyono and Rina Indrayani

+ Open abstract   ▤ View article   🅿 PDF

012113

User interface redesign of e-commerce platform mobile application (Kudo) through user experience evaluation to increase user attraction

Erlinda Muslim, Boy Nurtjahyo Moch, Yosua Wilgert, Fristya Fadhilah Utami and Dea Indriyani

+ Open abstract   ▤ View article   🅿 PDF

012114

Development of delivery consolidation procedures at courier service companies using Monte Carlo simulation

Dody Hartanto and Arsyad Bunyannudin

+ Open abstract   ▤ View article   🅿 PDF

012115

Effect of genotype and storage duration on taste and ecovalence of roasted beans of Arabica coffee (*Coffea arabica* L.)

Sabam Malau, Maria Rumondang Sihotang and Rosnawyta Simanjuntak

+ Open abstract   ▤ View article   🅿 PDF

Informatic Engineering & Technologies

012116

Impervious land classification using bootstrap principal component analysis

Janson Hendryli, Dyah Erny Herwindiati and Junita Merdi

Geographic information systems of fire vulnerability area in West Jakarta

N D Anggraini, D Trisnawarman, Wasino and D Arisandi

+ Open abstract   View article   PDF

Recommendation Product Based on Customer Categorization with K-Means Clustering Method

Bagus Mulyawan, M. Viny Christanti and Riyan Wenas

+ Open abstract   View article   PDF

Security system development for vehicle using the method of "mail notification" at villa Rizki Ilhami Tangerang residential

R Destriana, A A Permana, S D Legawa, Yanuardi and H Irawan

+ Open abstract   View article   PDF

Modeling the effects of social media, materialism, and car use habit on student's ridesharing behavior

Rudy Setiawan

+ Open abstract   View article   PDF

Low-cost array antenna design for S-Band maritime radar by using sparse array method

Efri Sandi, Ratna Addafiah and Pitoyo Yuliatmojo

+ Open abstract   View article   PDF

Fake Twitter Message Identification Using ECDSA Message Validation

Prasetyo Adi Wibowo Putro

+ Open abstract   View article   PDF

012128

Bid-Fish: An android application for online fish auction based on case study from Muara Angke, Indonesia

Amalia Nurul Balqis, Lianda Ramadhana, Rio Wirawan and Ika Nurlaili Isnainiyah

+ Open abstract   📄 View article   📕 PDF

012129

Performance comparison of reporting engine birt, jasper report, and crystal report on the process business intelligence

Bambang Prasetya Adhi, Dendy Nanda Prasetya and Widodo

+ Open abstract   📄 View article   📕 PDF

012130

Modeling on clinical group decision support system for screening and working diagnosis acute respiratory infections

Muhammad Syaukani, Sri Hartati, Hari Kusnanto and Suryo Guritno

+ Open abstract   📄 View article   📕 PDF

012131

Design and Theoretical Analysis of the Application of the Certificateless Public Key Encryption Scheme for Home Monitoring System Security

Hadyan Radifan and Amiruddin Amiruddin

+ Open abstract   📄 View article   📕 PDF

012132

Implementation of salsa20 stream cipher algorithm as an alternative cipher suite SSL-VPN for VOIP security

Aghnia Luthfy Nugrahtama and Yogha Restu Pramadi

+ Open abstract   📄 View article   📕 PDF

012133

Recording application with managerial prediction features for skenoo business

Aileen, Hery, Andree Emmanuel Widjaja, John Tampil Purba and Kristina Gloria Simanjuntak

+ Open abstract 　　　 📄 View article 　　　 📕 PDF

012134

Implementation of honeywords as a codeigniter library for a solution to password-cracking detection

Ardian Budi Kusuma and Yogha Restu Pramadi

+ Open abstract 　　　 📄 View article 　　　 📕 PDF

012135

A review of authentication protocols for rfid security on smart healthcare

Hanif Restu Dearfian and Amiruddin Amiruddin

+ Open abstract 　　　 📄 View article 　　　 📕 PDF

012136

Security Testing of a User-Participating Authentication Scheme Implementation on Web-Based Login System

Muhammad Akmaluddin and Yogha Restu Pramadiv

+ Open abstract 　　　 📄 View article 　　　 📕 PDF

012137

Website as an information system for distance learning how to build hydroponics with a greenhouse

Wiwin Windihastuty, Windarto and Samsinar

+ Open abstract 　　　 📄 View article 　　　 📕 PDF

012138

Prototipe of home security system using passive infra red and vibration sensor based android

Irma Saraswati, Reyndra Oktavfazrin and Rian Fahrizal

+ Open abstract 　　　 📄 View article 　　　 📕 PDF

Urgency of the Implementation of Health Technology Assessment to Support Indonesian National Health Security System

Gunawan Widjaja and Hotmaria H. Sijabat

+ Open abstract   🗏 View article   📄 PDF

       012145

Immense addition of royal jelly apis mellifera (ceiba pentandra) insufficient to increase fibroblast preputium proliferation

A Pramono, N Bustamam, M Amalia and M Sahlan

+ Open abstract   🗏 View article   📄 PDF

       012146

High tetragonula sp honey addition reduce cell proliferation on fibroblast preputium culture

M Shafira, A Pramono, N Nugrohowati and M Sahlan

+ Open abstract   🗏 View article   📄 PDF

       012147

The effect of tobacco leaves pyrolysis extract (*Nicotiana tabacum L.var. Virginia*) against the formation of biofilm by *Staphylococcusaureus*: An in-vitro study

D A Ario Putra, A Pramono, Anisah, A Fauzantoro and M Gozan

+ Open abstract   🗏 View article   📄 PDF

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Journal home

Journal scope

Information for organizers

Information for authors

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Proportional integral derivative DC motor speed control system for xy plane movements

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Proportional integral derivative DC motor speed control system for xy plane movements

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Abstract. DC motors are the most widely used electrical motors since their ease of use. Controlling a DC motor can be done by adjusting amount of voltage and current supplied to the motor. In this design the controlling is done using proportional integral derivative (PID) control, applied for movement in XY plane. Ziegler-Nichols method is used to determine PID constants. A Raspberry Pi is used to receive and process input from the user through a graphical user interface (GUI). The data input consists of two values, i.e. position and velocity. The GUI also shows the actual coordinate position on the screen. Two motors are controlled simultaneously by the Raspberry Pi through serial peripheral interface (SPI) with one microcontroller for each motor axis. The program contains a PID control algorithm to stabilize the motor speed. The coordination of the two stabilized motor speed is used to draw a sloping line. Sloping lines are drawn in order to determine the performance of the PID controller.

1. Introduction

Electrical motors are the most widely used electromechanical device in industry. It works by converting electrical energy to mechanical energy. The resulting mechanical energy can be used for rotating screws, pump impellers, fansor blowers, driving compressors, lifting materials, etc. There are two types of motors based on the electrical current used to drive the motors, i.e. alternating current (AC) motors and direct current (DC) motors. DC motors are more widely used since their rotation speed is easier to control compared to AC motors [1].

DC motor speed is controlled by varying the applied electrical voltage or current. Motor controlling is used so that the motor is able to be moved as desired, which in turn will be used for moving objects with a certain level of precision. Besides controlling motors to move in a particular speed, it must also have all basic controls in controlling motors such as start, stop, and completed with functions able to protect motors, machines, products and operators [2].

A lot of research has been done to create a motor controller system. The most frequently applied are fuzzy logic and proportional integral derivative (PID) method. Between the two methods, PID control is more widely used in the industry [3]. Based on all things above, then a motor controller using PID control method would be applied in the movements on xy-plane coordinates.

Comparison to other research was done before designing this system [4], [5]. The designed system is a DC motorcontrol with PID. The motor is then connected to the two motors to be used for moving the point coordinates in xy-plane. The moving point coordinates will leave a line like pattern. The line was measured. Its dimension was measured and compared to calculation result of two point coordinates entered. The ratio determines whether the PID controller works well or not. Other than that, the LCD display will show moving point coordinates when running. The point movement was also limited by point movements limit, limited by movement limiter module which would stop the motor when the point exceeds the maximum limit of allowed movements.

2. Design

The DC motor speed control system designed controls the coordinate point movements on xy-plane of the designed machine. The moving point coordinates draws a line with dimensions matched the input data entered by users. The line drawing with a desired gradient is performed by controlling the speed ratio of x and y-motor speed. The motor speed ratio can be expressed in the gradient equation of a straight line, i.e.:

$$\frac{Vy}{Vx} = m. \dots\dots\dots (1)$$

$$\frac{Vy}{Vx} = \frac{y_2 - y_1}{x_2 - x_1} \dots\dots\dots (2)$$

Dengan, v_y = motor speed in y-axis direction (m/s)

v_x = motor speed in y-axis direction (m/s)

$X1$ = value of x-axis coordinate of line starting point (m)

x_2 = value of x-axis coordinate of line ending point (m)

y_1 = value of y-axis coordinate of line starting point (m)

y_2 = value of y-axis coordinate of line ending point (m)

Equation (2) is applied to the drawing program by calculating the gradient of the origin point and the destination point. From equation (1), gradient and speed entered by the user are used to calculate the speed in each axis. The speed value entered by the user will be the highest speed value. A gradient value of larger than one (m>1) will cause y-axis motor speed becomes speed value entered by the user, while a gradient value of smaller than one (m<1) will cause x-axis motor speed becomes speed value entered by the user. The only exception occurs is when the straight line has zero or infinity gradient.

The motor speed is controlled using PID algorithm, which is an algorithm for reaching set point (SP) speed by calculating the difference between the actual value and the desired value. This value is calculated and stored in current error and previous error variables before it is multiplied by the constants. The PID constants are K_P, K_I dan K_D. Although there are only three constants but in order to determine them, systematic steps are needed, since anerrorwill cause the system to become unstable. The PID system isclosed loop [7].The block diagram of the closed loop system is shown in Figure 1.
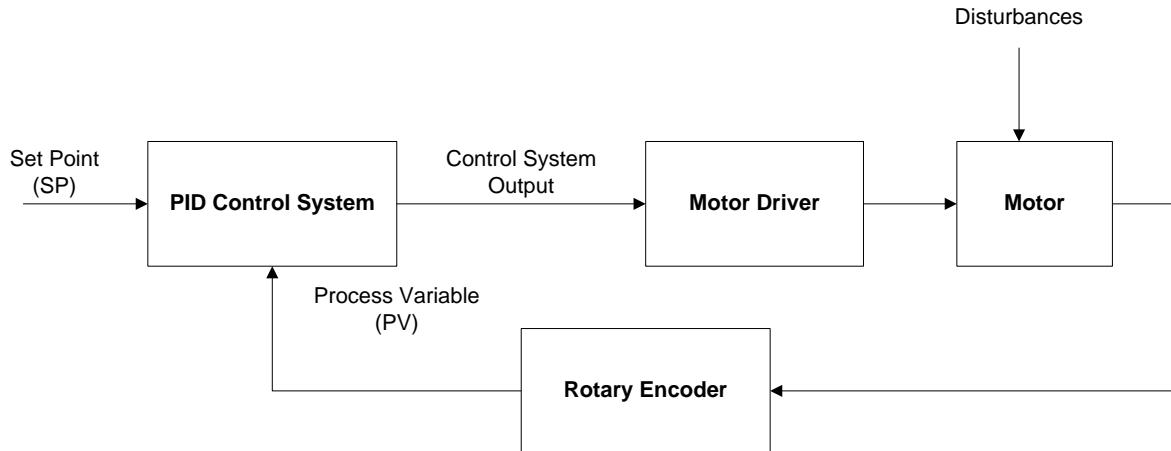
Figure 1. PID Block Diagram

The speed entered from the controller would be the SP, the purpose of the control system is for maintaining the motor speed at SP with the help of feedback from the rotary encoder. The value read from the encoder is called process variable (PV). The controlling will be done by calculating the error value from the difference between SP and PV. This error values are then added to produce the response. The system response is then sent to the motor driver to drive the motor.The PID algorithm is entered into the microcontroller. The PID algorithm needs to be changed first from continuous to discreet, so that it can be implemented in the program. Generally, the PID method equation is shown as follows:

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{de(t)}{dt}\right)$$

....

(3)

with, $u(t)$ = control system outputas a function oftime
            $e(t)$ = difference between SP and PV
            K = constant
            T_i = integral period
            T_d = differential period

Equation (3) is the PID equation for continuous system. In order to use it in discreet system, it should be transformed using Laplace and z-transform that can be derived as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d\frac{d}{dt}e(t)$$ ....(4)

with $K_p = K, K_i = \frac{K}{T_i}, K_d = KT_d$

Equation (4) is then Laplace transformed to:

$$G(s) = K_p + \frac{K_i}{s} + sK_d$$ ....(5)

The result of Laplace transform is then z-transformed to be used in discreet system. The result of the z-transform is as follows:

$$U(z) = \left[K_p + \frac{K_i}{1 - z^{-1}} + K_d(1 - z^{-1})\right]E(z)$$ ....(6)

Rearrangement of equation (6) gives:

$$U(z) = \left[\frac{(K_p + K_i + K_d) + (-K_p - 2K_d)z^{-1} + K_d z^{-2}}{1 - z^{-1}} \right] E(z) \dots\dots\dots(7)$$

By introducing new variables that contains each constant value, the following are obtained:

$$K_1 = K_p + K_i + K_d \;,\; K_2 = -K_p - 2K_d \;,\; K_3 = K_d$$

Equation (7) can be rewritten to:

$$U(z) - z^{-1}U(z) = [K_1 + K_2 z^{-1} + K_3 z^{-2}] E(z) \dots\dots\dots(8)$$

By performing inverse z-transform, the following equation is obtained:

$$u(t) = u[t-1] + K_1 e[t] + K_2 e[t-1] + K_3 e[t-2]\dots\dots\dots(9)$$

Equation (9) is ready to be applied to discreet system which will be programmed with

$u(t)$	= current control system output
$u[t-1]$	= control system output before $u(t)$
$e[t]$	= current error
$e[t-1]$	= error occurs before $e[t]$
$e[t-2]$	= error occurs before $e[t-1]$
K_1	$= K_p + K_i + K_d$
K_2	$= -K_p - 2K_d$
K_3	$= K_d$

The program segment for the microcontroller written based on equation (9) is as follows:

```
1   void PID()
2   {
2     if (input_kecepatan!=0) setpoint = input_kecepatan;
4   e2=e1;
5   e1=e;
6   pv=abs(rpm);
7   e=setpoint-pv;
8   outputpwm= outputpwm + k1*e + k2*e1 + k3*e2;
9   if(outputpwm>OUTPUTMAX)
10  outputpwm=OUTPUTMAX;
11  else if(outputpwm<OUTPUTMIN)
12  outputpwm= OUTPUTMIN;
13  OCR1A=(int)outputpwm;
14  }
```

The PID procedure is called each time the motor rpm value is updated. *The* rpm value in line 6 is obtained from counting external encoder interrupt called by Overflow Interrupt Timer 0 every 120 ms. The program changes the PWM output values by changing the OCR1A value. In line 8, change in PWM depends on the values of k1, k2, and k3 obtained from the tuning result using Ziegler-Nichols method added to the previous PWM output. PWM mode used in the program is the Phase Correct Mode. Line 9-12 limits the PWM output value so that it does not exceed the maximum value that can be stored in OCR1A register. The flowchart is shown in Figure 2.
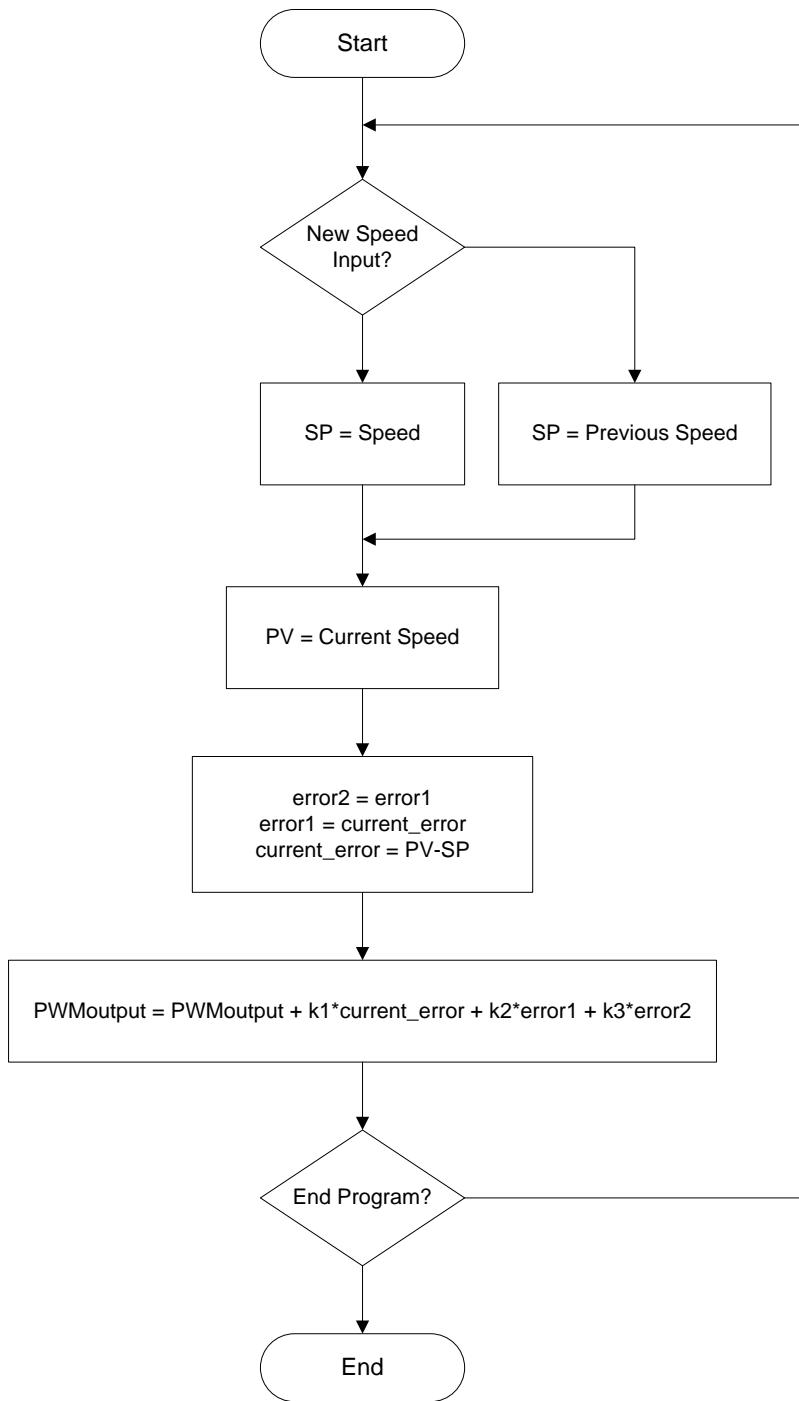
Figure 2. PID software flowchart

The PID constants selection used is the Ziegler-Nichols method. This method has been applied in a lot of industrial machinery PID control and a lot of other PID methods are developed based on this method. The Ziegler-Nichols method gets the tuning values from experiments simulated in a real system or simulated system [8].

The tuning procedure consists of five steps, i.e.:

1. The value in SP is assigned with a value that is the machine's working value. Then, make the process in the system approaching SP by controlling the PV value until the difference is 0.

2. Change the PID controller to P controller by assigning values to $T_I=0$ and $T_D=0$.
3. The K_P value is increased slowly until the system oscillates. The K_P instantaneous value before oscillation is measured. The measured value is called critical gain (K_C).
4. The next value measured isthe oscillation periode (T_C). This value is obtained by recording the time when oscillation first occurs.
5. After the two values are obtained, the PID parameter values are determined based on the Ziegler-Nichols table shown in Table1.

Table 1. Ziegler-Nichols formula for closed loop method controller [8]

Controller Type	K_P	T_I	T_D
P *Controller*	0.5 K_C	0	0
PI *Controller*	0.45 K_C	0.833 T_C	0
PID *Controller*	0.6 K_C	0.5 T_C	0.125T_C

The values $K_I = 1/T_I$ and $K_D = 1/T_D$ are obtained from Table 1.

The drawn line data is entered by the user using the graphical user interfaces (GUI) made in the Raspberry Pi. The display program displays the machine coordinate point and the actual machine condition. The inputs of the program are sent through SPI communication to operate the machine. The program is written in Python 2.7.1 language. The widgets in the GUI are made using GTK+3 modules with the help of Glade Interface Designer3.14.2 software. The GUI display is shown in Figure 3.
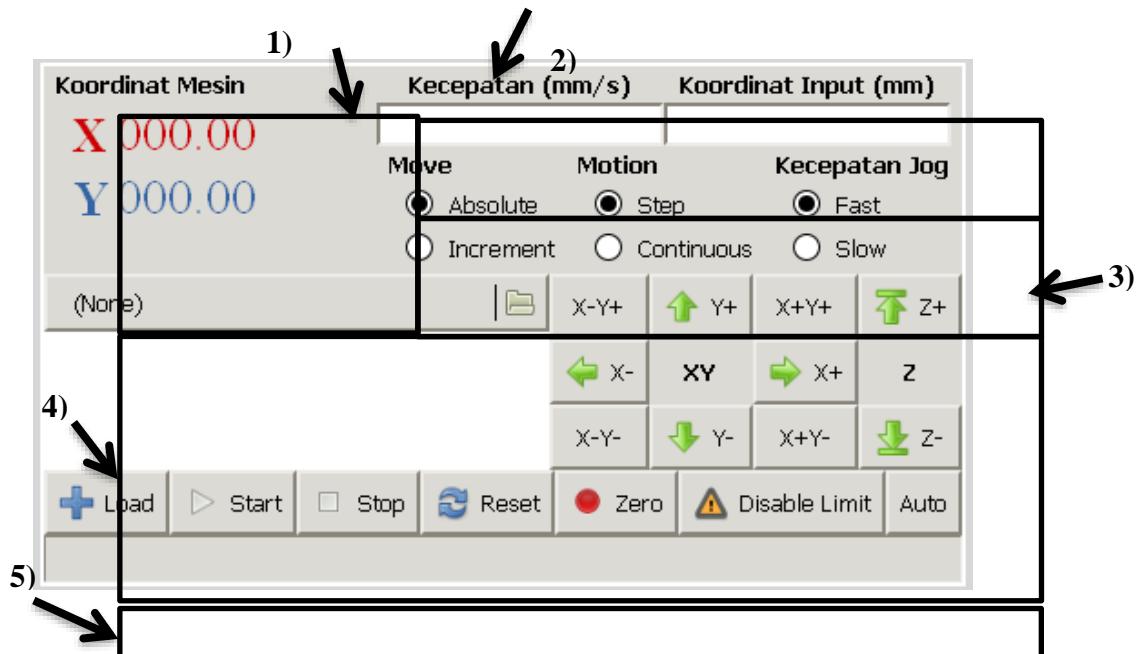
Figure 3. GUI of the machine

The GUI of the machine consists of several rooms, i.e.:
1. Display room
2. Input room

3. Option Button room
4. Button room
5. Status Bar room

The display room updates the coordinate values of the machine every 100 ms. The input room accepts inputs from user and checks the correctness of input format. The speed format must be a positive number less than 100 mm/s, while the coordinate input format is "x value, y value". The values of x and y entered must be less than 1000.

The radio button room is provided for selection of modes to be used which matches the frame title. The radio button move group is used for controlling the coordinate movement type. Selecting absolute mode will send the destination value of the machine according to the coordinates entered. The increment mode is used for sending the destination value of the sum ofcurrent position value and input coordinate value. The selection of radio button motion group is used for controlling the pushed jog button. Selecting step mode will run the machine when one of the jog or direction button is pushed and stop the machine when it is released. Continuous mode selection runs the machine when one of the jog button is pressed and would only stop when the stop button is pressed. The radio button group jog speed controls the machine movement speed when it is moving using the jog button.

The button room is used for controlling the machine, both automatically and manually. The program runs in two modes, i.e. auto and manual. When auto button is selected, all buttons that is running the machine directly and related radio button will not function, while when manual button is selected, start button, stop button, movement control radio button speed value input, and coordinate will not function. Status bar room displays machine condition. The function of each part is shown in Figure 4.
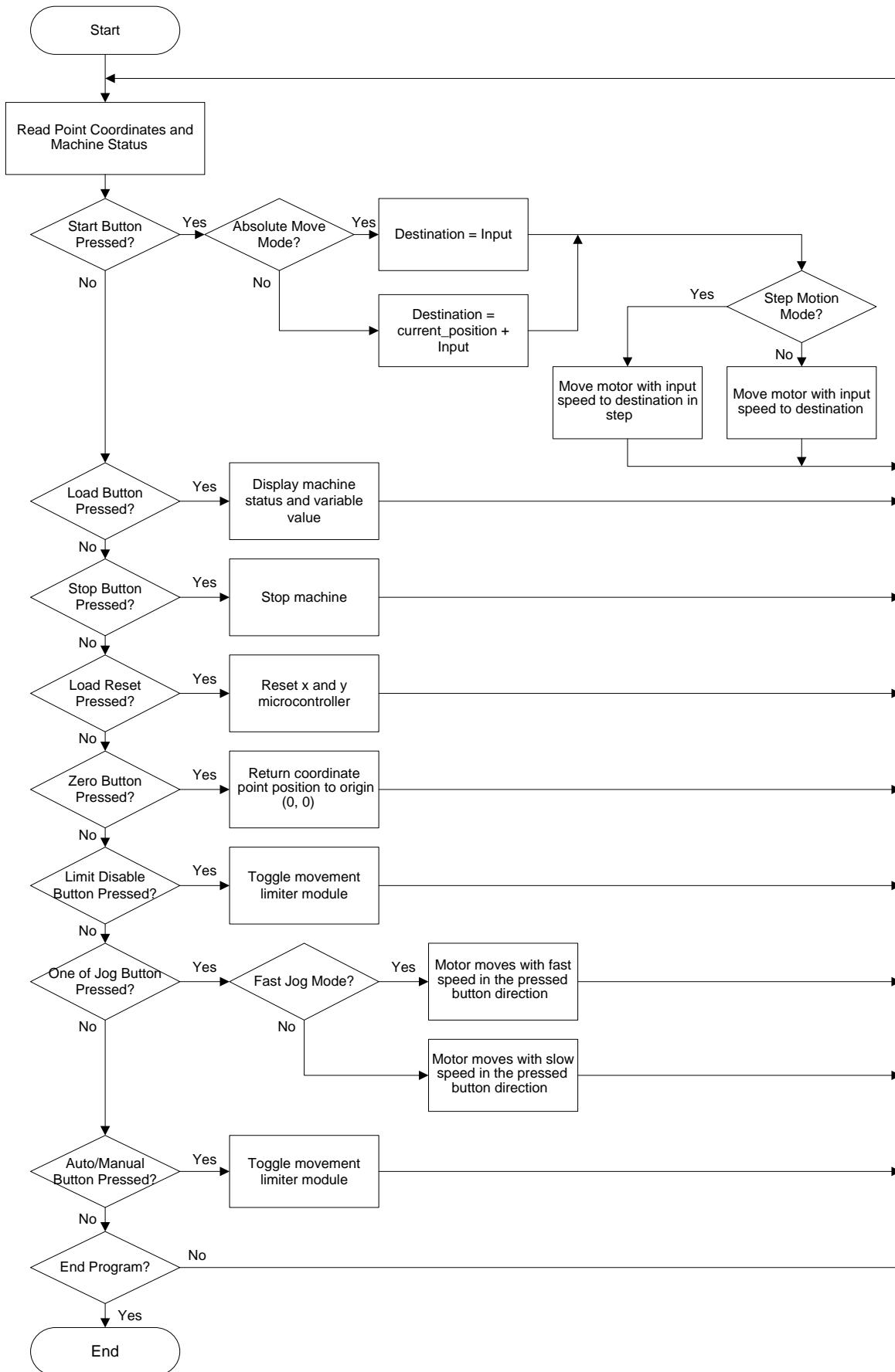
Figure 4. Program flowchart for display and input

Based on the concept description above, a block diagram is provided in order to show the interconnection between modules and make the design easier. The block diagram is shown in Figure5.
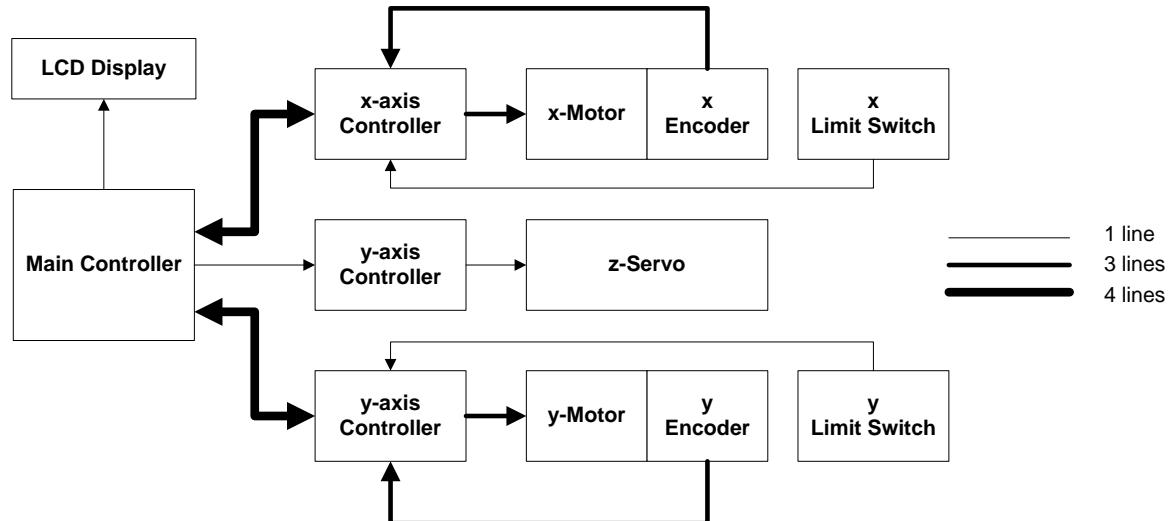
Gambar 5. System block diagram

3. Testing and Analysis

Testing was performed on each module to simplify troubleshooting when a failure in a particular module causes system malfunction. The overall system was performed after all the modules passed the test and the modules are connected together. Therotary encoder module testing is performed by rotating the motor manually in particular positions and counting the number of pulses produced. The motor was rotated to 45^0, 90^0, 180^0, and 360^0 angles. A simple program in the microcontroller is used for counting the number of pulses from the encoder. The rotary encoder used in the design produces 500 pulses per cycle. The rotary encoder readings was recorded in Table 2.

Table2. Rotary Encoder Test Results

Angle of Rotation (^{0})	Number of pulses read from rotary encoder
45	64
90	124
180	251
360	500

Based on Table 2, the pulse reading is then converted back to degrees using the following equation:

$$Position = \frac{pulses\ read}{number\ of\ pulses\ in\ one\ cycle} \; x \; 360^0$$

....(10)

Using equation (10), the position obtained from the first reading was 46.08^0. The second reading was 89.28^0, the second reading was180.72^0, and the last reading was 360^0. The maximum percentage average of reading error is 2.4% on first reading. The errors occurred because of parallax error caused by the view angle that was not orthogonal.

The DC motor testing was performed to make sure it worked properly. The testing was performed by measuring maximum rotation speed and current used by the DC motor. Maximum rotation speed was obtained by connecting the motor directly to the 24 V_{DC} power supply. The test results were the DC motor maximum rotation speed used by the x-motor was 892 RPM and for y-motor is 776 RPM. The total current consumption for the 2 motors was 3.5 A. That amount of total current is within the capacity of the power supply module.

Limit switch was tested by measuring its resistance. Limit switchused is the normally closed type. Limit switch is good if the resistance is close to 0 (zero) when it is not pushed. On the other hand when it is not pushed, the resistance value is very large. The test results gave a resistance value of 15.72 kOhm when not pushed, and 0 Ohm when pushed.

The motor driver module testing is performed in two parts. In the first part the PWM output was given by the microcontroller to the motor and the RPM result was measured. The rotation direction and stopping of the motor was also performed in the first part. The test is successful if the motor speed increases when the given PWM value increases. The result of motor driver module testing controlling the DC motor speed is shown in Table 3. The motor driver must also be able to change the rotation direction of the motor and stop the motor. The motor driver module test result in driving the DC motor is shown in Table 4.

Tabel 3. Motor driver module on speed control test result

DC Motor	Motor driver PW input	Rotary encoder reading (RPM)
Motor X	50	114
	100	187
	250	325
	500	566
	1000	887
Motor Y	50	89
	100	109
	250	244
	500	476
	1000	758

Tabel 4. Motor driver module on movement control test result

Driver Motor Input		Motor movements
Input 1	*Input* 2	
0	0	Stopping without braking
0	1	Rotating in clockwise direction
1	0	Rotating in counter clockwise direction
1	1	Stopping by braking electronically

The second stage of testing is performed by using the PID algorithm in the microcontroller for controlling motor speed in a certain set point. The testing would be successful when the PID algorithm was able to maintain the motor speed and performance criteria was sufficiently good. The testing was performed by using PID constants obtained by trials. The PID response graphic is shown in Figure 6.
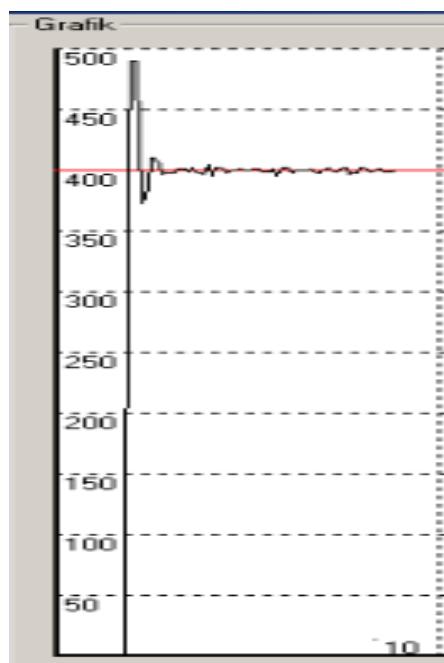
Figure 6. PID responsegraphic

The graphic was drawn by sending the processed data to a computer through serial communication. The computer program used was written using Visual Basic 6.0software. The PID constants used are K_P=1, K_I=0.24, and K_D=0.11. These values were obtained using the Ziegler Nichols method in Table 2, Kc = 1.67 and Tc = 0.24. The motor driver with PID modul test result is shown in Table 5.

Table 5. Motordriver with PIDmodul test result

Set Point	Speed when stable(rpm)	Rise Time(seconds)	Settling Time(seconds)	Steady State Error(%)	Overshoot(%)
100	105	0,3	1	5	28
200	196	0,5	1,4	2	24
300	298	0,8	1,5	0,6	23
400	401	1	1,9	0.25	20

As seen in Table 5, the overshoot values do not show good performance criteria, i.e. 5%. This will affect significantly if the movements performed is movements per millimeter, but the overshoot value does not affect movements in cm. All others achieved good performance criteria, i.e. maximum rise time of 1 second, maximum settling time of 2 seconds, and maximum steady state error of 5%.

Overall system testing was performed to make sure that the whole system work properly when all modules are integrated together. It started by entering the desired point coordinates input through the GUI. The input data was then sent to each controller andthe z-plane servo motor moved the plate down. The x and y axis motor controller moved the DC motor at the desired speed. The movements drew a line on the work plate. The motor stopped when the desired point coordinates was reached and the z-servo motor lifted the work plate up. The overall system test result is shown in Table 6. As seen in Table 6, there is some error between the drawn line and the input data. The maximum error is 1.3 mm as displayed on theLCD display, using a ruler it is1 mm. The sloping line with gradient had jagged edges since the mechanical part for Y axis experiences vibration when the motor is moving. The accuracy level obtained in this design is ±1 mm. The test results shows that the designed system is able to work as expected, the motor can be controlled to drive movements in both axis and has the correct dimension just like the data input to the system.

Table 6. Complete system test result

Input (mm)		Speed Input (mm/s)	Drawn Line	Display (mm)		Measuring Result (mm)	
X	Y			X	Y	X	Y
0	100	40	Parallel toy-axis	0	100,78	0	100,5
100	100	40	Parallel to x-axis	100,34	0	100	0
100	100	10	Sloping line with gradient 1	99,44	101,03	99,5	101
-100	-200	10	Sloping line with gradient2	-99,3	-199,8	-99	-99,200

4. Conclusion

Based on the test performed on the designed PID based motor speed control system, it can be concluded that among others:

1. The motor speed can be controlled until the speed is stable using PID. The motor stable condition can be reached in less than 2 seconds on average and the error when the condition is stable is less than 5% of the required speed. The performance criteria that is not achieved yet in the PID control is the maximum overshoot of the motor speed control system, as it exceeds 5%.

2. The accuracy of the designed system is ± 1 mm, since the microcontroller controls the speed every 120 ms. Therefore, if the speed used is 10 mm/s, then the maximum error occurred when the motor rotates before it is stopped is 1.2 mm.

3. The drawn sloping line is not straight and has jagged edge, since y-axis part vibrates when it moves. The pen connected to z-axis would be affected by the vibration. Therefore, sometimes it does not touch the working table. The vibration also cause the drawn line to be not straight since the y-motor speed becomes difficult to control.

5. References

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