Source details

Telkomnika (Telecommunication Computing Electronics and Control)

Scopus coverage years: from 2011 to Present

Publisher: Universitas Ahmad Dahlan

ISSN: 1693-6930 E-ISSN: 2087-278X

Subject area: Engineering: Electrical and Electronic Engineering

Source type: Journal

CiteScore 2020
2.2

SJR 2020
0.258

SNIP 2020
0.746

View all documents > Set document alert Save to source list Source Homepage

CiteScore CiteScore rank & trend Scopus content coverage

i Improved CiteScore methodology

CiteScore 2020 counts the citations received in 2017-2020 to articles, reviews, conference papers, book chapters and data papers published in 2017-2020, and divides this by the number of publications published in 2017-2020. Learn more >

CiteScore 2020

2.2 = 2,987 Citations 2017 - 2020 / 1,360 Documents 2017 - 2020

Calculated on 05 May, 2021

CiteScoreTracker 2021

2.9 = 3,993 Citations to date / 1,385 Documents to date

Last updated on 06 April, 2022 • Updated monthly

CiteScore rank 2020

Category	Rank	Percentile
Engineering — Electrical and Electronic Engineering	#373/693	46th

View CiteScore methodology > CiteScore FAQ > Add CiteScore to your site

Telkomnika (Telecommunication Computing Electronics and Control) • *Open Access* • Volume 18, Issue 2, Pages 1021 - 1029 •
1 April 2020

Document type
Article • *Green Open Access*

Source type
Journal

ISSN
16936930

DOI
10.12928/TELKOMNIKA.V18I2.14749

Joint control of a robotic arm using particle swarm optimization based H_2/H_∞ robust control on arduino

Sutyasadi, Petrus ; Wicaksono, Martinus Bagus

Save all to author list

[a] Politeknik Mekatronika Sanata Dharma, Indonesia

Abstract

Author keywords

Sustainable Development Goals 2021

SciVal Topics

Metrics

Funding details

Abstract

This paper proposes a small structure of robust controller to control robotic arm's joints where exist some uncertainties and unmodelled dynamics. Robotic arm is widely used now in the era of Industry 4.0. Nevertheless, the cost for an industry to migrate from a conventional automatic machine to industrial robot still very high. This become a significant challenge to middle or small size industry. Development of a low cost industrial robotic arm can be one of good solutions for them. However, a low-cost manipulator can bring more uncertainties. There might be exist more unmodelled dynamic in a low-cost system. A good controller to overcome such uncertainties and unmodelled dynamics is robust controller. A low-cost robotic arm might use small or medium size embedded controller such as Arduino. Therefore, the control algorithm should be a small order of controller. The synthesized controller was tested using MATLAB and then implemented on the real hardware to control a robotic manipulator. Both the simulation and the experiment showed that the proposed controller performed satisfactory results. It can control the joint position to the desired position even in the presence of

uncertainties such as unmodelled dynamics and variation of loads or manipulator poses.

Joint cont...

View PDF

Full text options

Export

Author keywords

Arduino; H_2/H_∞ robust control; Robotic arm

Sustainable Development Goals 2021 New

SciVal Topics

Metrics

Funding details

References (26)

View in search results format >

All

CSV export Print E-mail Save to PDF

Create bibliography

1 Apkarian, Pierre, Gahinet, Pascal, Becker, Greg
Self-scheduled H_∞ control of linear parameter-varying systems
(1994) *Proceedings of the American Control Conference*, 1, pp. 856-860. Cited 60 times.
View at Publisher

2 Apkarian, P., Adams, R.J.
Advanced gain-scheduling techniques for uncertain systems
(1998) *IEEE Transactions on Control Systems Technology*, 6 (1), pp. 21-32. Cited 757 times.
doi: 10.1109/87.654874
View at Publisher

3 Angelis, G.
(2001) *System Analysis, modelling and control with polytopic linear models-PhD thesis*. Cited 49 times.
Technische Universiteit Eindhoven, The Netherlands

4 Montagner, V.F., Oliveira, R.C.L.F., Leite, V.J.S., Peres, P.L.D.
LMI approach for H_∞ linear parameter-varying state feedback control
(2005) *IEE Proceedings: Control Theory and Applications*, 152 (2), pp. 195-201. Cited 72 times.
doi: 10.1049/ip-cta:20045117
View at Publisher

5 Namerikawa, Toru, Fujita, Masayuki, Matsumura, Fumio
H_{INF} control of a robot manipulator using a linear parameter varying representation
(1997) *Proceedings of the American Control Conference*, 1, pp. 111-112. Cited 4 times.

6 Kang, Zibo, Yin, Yingjie, Fujii, Seizo, Chai, Tianyou
Gain-scheduling H_{INF} vibration control for SCARA type robot manipulators via LMIs

(1997) *Proceedings of the American Control Conference*, 1, pp. 106-110. Cited 6 times.

7 Kang, Z.B., Chai, T.Y., Oshima, K., Yang, J.M., Fujii, S.
Robust vibration control for SCARA-type robot manipulators

(1997) *Control Engineering Practice*, 5 (7), pp. 907-917. Cited 26 times.
www.elsevier.com/inca/publications/store/1/2/3/
doi: 10.1016/S0967-0661(97)00078-6

View at Publisher

8 Yu, Z., Chen, H., Woo, P.-Y.
Gain scheduled LPV H∞ control based on LMI approach for a robotic manipulator

(2002) *Journal of Robotic Systems*, 19 (12), pp. 585-593. Cited 47 times.
doi: 10.1002/rob.10062

View at Publisher

9 Ali, H.S., Boutat-Baddas, L., Becis-Aubry, Y., Darouach, M.
(2006) *H-infinity control of a SCARA robot using polytopic LPV approach*

10 Axelsson, P., Helmersson, A., Norrlöf, M.
H_{∞}-controller design methods applied to one joint of a flexible industrial manipulator (Open Access)

(2014) *IFAC Proceedings Volumes (IFAC-PapersOnline)*, 19, pp. 210-216. Cited 10 times.
http://www.ifac-papersonline.net/browser?browse=c
ISBN: 978-390282362-5
doi: 10.3182/20140824-6-za-1003.00143

View at Publisher

11 Aoi, S.
Simple legged robots that reveal biomechanical and neuromechanical functions in locomotion dynamics
(Open Access)

(2014) *Journal of Robotics and Mechatronics*, 26 (1), pp. 98-99. Cited 2 times.
http://www.fujipress.jp/finder/access_check.php?pdf_filename=ROBOT002600010013.pdf&frompage=abst_page&errormode=Login&pid=5020&lang=English
doi: 10.20965/jrm.2014.p0098

View at Publisher

12 Fukuoka, Y., Katabuchi, H., Kimura, H.
Dynamic Locomotion of Quadrupeds Tekken 3&4 Using Simple Navigation
(2010) *Journal of Robotics and Mechatronics*, 22 (1), pp. 36-42. Cited 12 times.

13 Zang, Z.G., Kimura, H., Fukuoka, Y.
Self-Stabilizing Dynamics for a Quadruped Robot and Extension Toward Running on Rough Terrain
(2007) *Journal ofRobotics and Mechatronics*, 19 (1), pp. 3-12. Cited 7 times.

14 Mamiya, S., Sano, S., Uchiyama, N.

Foot structure with divided flat soles and springs for legged robots and experimental verification (Open Access)

(2016) *Journal of Robotics and Mechatronics*, 28 (6), pp. 799-807. Cited 2 times.
https://www.fujipress.jp/main/wp-content/themes/Fujipress/pdf_subscribed.php
doi: 10.20965/jrm.2016.p0799

View at Publisher

15 Sutyasadi, P., Parnichkun, M.

Gait Tracking Control of Quadruped Robot Using Differential Evolution Based Structure Specified Mixed Sensitivity H ∞ Robust Control (Open Access)

(2016) *Journal of Control Science and Engineering*, 2016, art. no. 8760215. Cited 12 times.
http://www.hindawi.com/journals/jcse
doi: 10.1155/2016/8760215

View at Publisher

16 Lekkala, K.K., Mittal, V.K.

PID controlled 2D precision robot

(2014) *2014 International Conference on Control, Instrumentation, Communication and Computational Technologies, ICCICCT 2014*, art. no. 6993133, pp. 1141-1145. Cited 5 times.
ISBN: 978-147994190-2
doi: 10.1109/ICCICCT.2014.6993133

View at Publisher

17 Khairudin, M., Mohamed, Z., Husain, A.R.

Dynamic model and robust control of flexible link robot manipulator (Open Access)

(2011) *Telkomnika*, 9 (2), pp. 279-286. Cited 42 times.
http://journal.uad.ac.id/index.php/TELKOMNIKA/issue/archive
doi: 10.12928/telkomnika.v9i2.698

View at Publisher

18 Tumari, M.Z.M., Subki, A.S.R.A., Aras, M.S.M., Kasno, M.'A., Ahmad, M.A., Suid, M.H.

H-infinity controller with graphical LMI region profile for liquid slosh suppression (Open Access)

(2019) *Telkomnika (Telecommunication Computing Electronics and Control)*, 17 (5), pp. 2636-2642. Cited 6 times.
http://journal.uad.ac.id/index.php?journal=TELKOMNIKA&page=issue&op=archive
doi: 10.12928/TELKOMNIKA.v17i5.11252

View at Publisher

19 Mousmi, A., Abbou, A., El Houm, Y.

Real-time implementation of a novel hybrid fuzzy sliding mode control of a BLDC motor

(2019) *International Journal of Power Electronics and Drive Systems*, 10 (3), pp. 1167-1177. Cited 5 times.
http://ijpeds.iaescore.com/index.php/IJPEDS
doi: 10.11591/ijpeds.v10.i3.1167-1177

View at Publisher

Joint cont...

View PDF

Full text options

Export

20 Tarmizi, Y., Jidin, A., Karim, K.A., Sutikno, T.
A simple constant switching frequency of direct torque control of brushless DC motor

(2019) *International Journal of Power Electronics and Drive Systems*, 10 (1), pp. 10-18. Cited 10 times.
http://www.iaescore.com/journals/index.php/IJPEDS/article/download/14947/10656
doi: 10.11591/ijpeds.v10n1.pp10-18

View at Publisher

21 Santos, P.G., Garcia, E., Estreera, J.
Quadrupedal Locomotion
(2006) *Springer*

22 Pambudi, W.S., Alfianto, E., Rachman, A., Hapsari, D.P.
Simulation design of trajectory planning robot manipulator (Open Access)

(2019) *Bulletin of Electrical Engineering and Informatics*, 8 (1), pp. 196-205. Cited 12 times.
http://journal.portalgaruda.org/index.php/EEI/article/download/1179/1022
doi: 10.11591/eei.v8i1.1179

View at Publisher

23 Skogestad, S., Postlethwaite, I.
Multivariable Feedback Control
(2001) *New York: John Wiley & Sons*. Cited 6 times.

24 Kennedy, James, Eberhart, Russell
Particle swarm optimization

(1995) *IEEE International Conference on Neural Networks - Conference Proceedings*, 4, pp. 1942-1948. Cited 47234 times.

25 Harun, S., Ibrahim, M.F.
A genetic algorithm based task scheduling system for logistics service robots (Open Access)

(2019) *Bulletin of Electrical Engineering and Informatics*, 8 (1), pp. 206-213. Cited 13 times.
http://journal.portalgaruda.org/index.php/EEI/article/download/1437/1023
doi: 10.11591/eei.v8i1.1437

View at Publisher

26 Mahamed, H.W.A.
(2018) *Designing and implementation of PID controller robotic arm*
Dissertation, Sudan University of Science and Technology, College of Graduate Studies

Sutyasadi, P.; Politeknik Mekatronika Sanata Dharma, Paingan, Maguwoharjo, Depok, Sleman, Yogyakarta, Indonesia; email:peter@pmsd.ac.id

About Scopus

What is Scopus

Content coverage

Scopus blog

Scopus API

Privacy matters

Language

日本語に切り替える

切換到简体中文

切換到繁體中文

Русский язык

Customer Service

Help

Tutorials

Contact us

Telkomnika (Telecommunication Computing Electronics and Control)

COUNTRY

Indonesia

Universities and research institutions in Indonesia

SUBJECT AREA AND CATEGORY

Engineering
- Electrical and Electronic Engineering

PUBLISHER

Universitas Ahmad Dahlan

H-INDEX

22

PUBLICATION TYPE

Journals

ISSN

16936930, 2087278X

COVERAGE

2011-2021

INFORMATION

Homepage

How to publish in this journal

telkomnika@ee.uad.ac.id

SCOPE

TELKOMNIKA (Telecommunication Computing Electronics and Control) is a peer reviewed International Journal in English published four issues per year (March, June, September and December). The aim of TELKOMNIKA is to publish high-quality articles dedicated to all aspects of the latest outstanding developments in the field of electrical engineering. Its scope encompasses the engineering of signal processing, electrical (power), electronics, instrumentation & control, telecommunication, computing and informatics which covers, but not limited to, the following scope: Signal Processing[...] Electronics[...] Electrical[...] Telecommunication[...] Instrumentation & Control[...] Computing and Informatics[...]

Quartiles

FIND SIMILAR JOURNALS

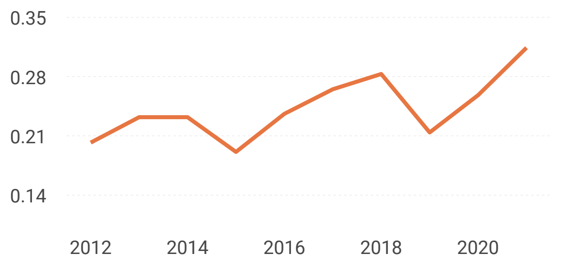
1
Indonesian Journal of Electrical Engineering and
IDN
48%
similarity

2
Indonesian Journal of Electrical Engineering and
IDN
46%
similarity

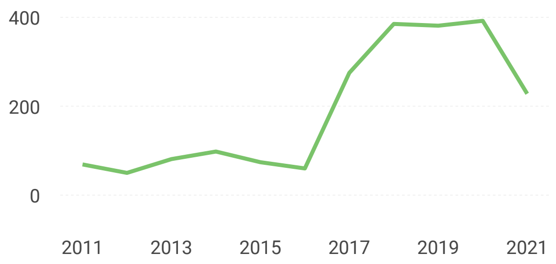
3
Bulletin of Electrical Engineering and Informatics
IDN
44%
similarity

4
Internationa Electrical an
IDN
4
s

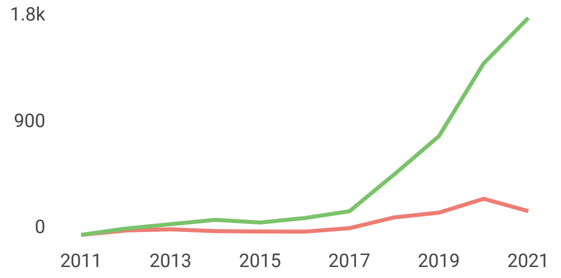
SJR



Total Documents

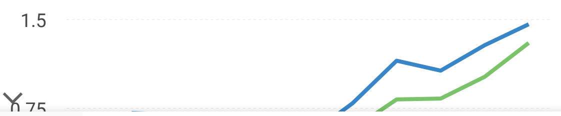


Total Cites Self-Cites

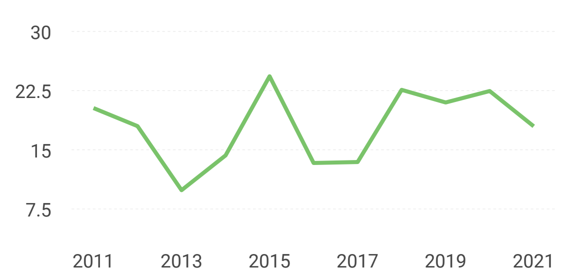


Citations per document

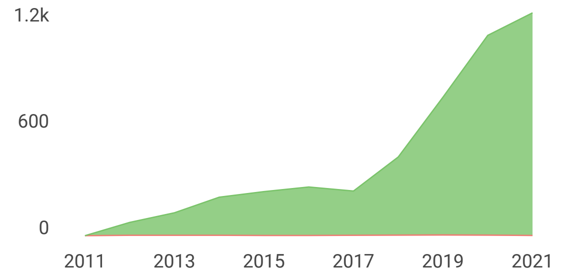
External Cites per Doc Cites per Doc



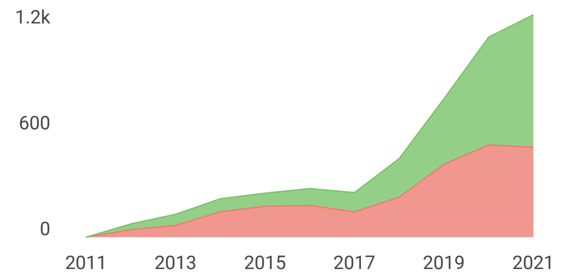
% International Collaboration



Citable documents Non-citable documents



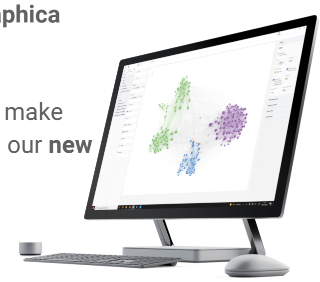
Cited documents Uncited documents



← Show this widget in your own website

Just copy the code below and paste within your html code:

<a href="https://www.scimag



Metrics based on Scopus® data as of April 2022

J **jancokers** 3 months ago

Why is this journal still indexed by Scopus? even though it still contains unqualified journals

reply

SCImago Team

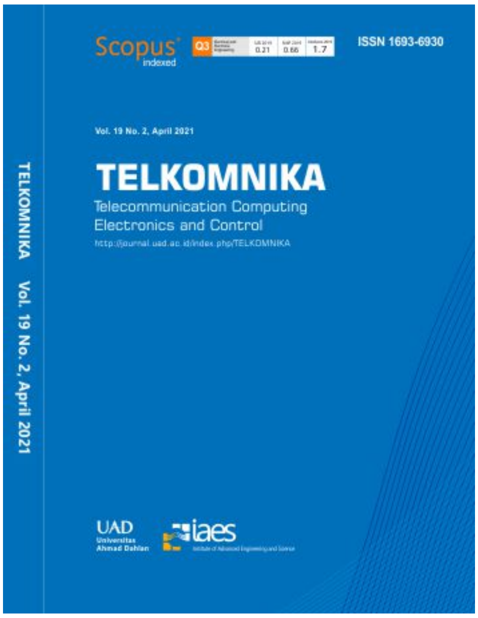
Melanie Ortiz 3 months ago

Dear Jancokers, thank you very much for your comment. We suggest you consult the Scopus database directly. Keep in mind that the SJR is a static image (the update is made one time per year) of a database (Scopus) which is changing every day.
Best Regards, SCImago Team

UAD Universitas Ahmad Dahlan
TELKOMNIKA
(Telecommunication Computing Electronics and Control)
http://journal.uad.ac.id/index.php/TELKOMNIKA
ISSN 1693-6930, e-ISSN 2302-9293
SJR SCImago Journal & Country Rank
Q3 Electrical and Electronic Engineering SJR 2020 0.258

TELKOMNIKA (Telecommunication Computing Electronics and Control)

TELKOMNIKA (Telecommunication, Computing, Electronics and Control) ISSN: 1693-6930, e-ISSN: 2302-9293 is a peer-reviewed, scientific journal published by Universitas Ahmad Dahlan (UAD) *in collaboration with* Institute of Advanced Engineering and Science (IAES). The aim of this journal is to publish high-quality articles dedicated to all aspects of the latest outstanding developments in the field of electrical & electronics engineering and computer science. Its scope encompasses the applications of Telecommunication, Computing, Electrical & Electronics, and Instrumentation & Control. It was first published in 2003. Beginning with issue 1 of volume 16 (2018), TELKOMNIKA will be published as a bimonthly journal (6 issues/year). The journal registered in the CrossRef system with Digital Object Identifier (DOI) prefix 10.12928. The Journal has been indexed by SCOPUS, Google Scholar, Scholar Metrics etc; accredited 'A' Grade by DGHE (Ministry of Research, Technology and Higher Education, Republic of Indonesia); registered BASE - Bielefeld Academic Search Engine and CORE KMi, etc. The Journal also have a license agreement with ProQuest LLC and EBSCO Publishing.



A submitted paper should be an original work, and should not have been presented or published previously. Submission for publication in this journal presumes that the paper is not being considered for publication elsewhere and is not under review by any other publication. All articles undergo a thorough evaluation process while following all ethical guidelines to maintain the highest publishing standards. The TELKOMNIKA Team strictly review suitability, originality of manuscripts for publication. Our Editors maintain transparency of research, assess manuscript for scientific value, ensure that content is free from any manifestations of discrimination, and evaluate information objectively without any conflict of interests. **Publication integrity is one of the principle responsibilities we take.** Beginning with **issue 1** of **volume 20 (2022), TELKOMNIKA** will publish about **25 manuscripts ONLY** per **issue** (or about **150 manuscripts** per **year**).

Authors should submit only papers that have been carefully proofread and polished. Manuscripts are accepted with the understanding that they are an original or extended version of previously published papers in conferences and/or journals and that, if the work received an official sponsorship, it has been duly released for open publication. Before submission please make sure that your paper is prepared using the journal paper template. The authors must refer to TELKOMNIKA Journal for writing format and style (Please download and use as a template for initial manuscript submission in .DOCX or LATEX). This will ensure fast processing and publication. Any papers not fulfilling the requirements based on the guideline to authors will not be processed.

Submit

If you have any problems with the online submission, please do email to telkomnika [at] uad.ac.id (subject: Your Name_Problem with Online Submission), and cc: telkomnika [at] journal.uad.ac.id.

Announcements

Improving Quality of the TELKOMNIKA

Dear Authors,

In **2022**, we plan to publish **6 issues** *(as in 2018-2021)*, and **each issue is about 25 papers**. We will publish high quality original/research articles only, and some review papers by invitation. We intend to maintain, improve the high standards of excellence, visibility and further develop of the journal. The goal is to maintain journal indexation in the Scopus and to get indexation in the Web of Science, with the continuous increasing the quality of the journal articles and visibility of the journal.

USER
Username
Password
Remember me
Login

TEMPLATE
TELKOMNIKA TEMPLATE

ONLINE SUBMISSION
Submit Paper

QUICK LINKS
- Author Guideline
- Editorial Boards
- Reviewers
- **Online Submission**
- Abstracting and Indexing
- Scopus: Add missing document
- Publication Ethics
- Visitor Statistics
- Contact Us

Scimago Journal Rank (SJR) of TELKOMNIKA

JOURNAL CONTENT
Search
Search Scope
All
Search

Browse
- By Issue
- By Author
- By Title

UAD Universitas Ahmad Dahlan

TELKOMNIKA
(Telecommunication Computing Electronics and Control)

http://journal.uad.ac.id/index.php/TELKOMNIKA
ISSN 1693-6930, e-ISSN 2302-9293

SJR SCImago Journal & Country Rank
Q3 Electrical and Electronic Engineering SJR 2020 0.258

HOME ABOUT LOGIN REGISTER SEARCH CURRENT ARCHIVES ANNOUNCEMENTS

Home > **Editorial Team**

Editorial Team

USER

Username
Password
Remember me
Login

TEMPLATE

TELKOMNIKA TEMPLATE

ONLINE SUBMISSION

Submit Paper

QUICK LINKS

- Author Guideline
- Editorial Boards
- Reviewers
- **Online Submission**
- Abstracting and Indexing
- Scopus: Add missing document
- Publication Ethics
- Visitor Statistics
- Contact Us

Scimago Journal Rank (SJR) of TELKOMNIKA

Telkomnika (Telecommunication...
Q3 Electrical and Electronic Engineering best quartile
SJR 2021 0.31
powered by scimagojr.com

JOURNAL CONTENT

Search

Search Scope
All
Search

Browse
- By Issue
- By Author
- By Title

TELKOMNIKA Telecommunication, Computing, Electronics and Control
ISSN: 1693-6930, e-ISSN: 2302-9293
Universitas Ahmad Dahlan, 4th Campus
Jl. Ringroad Selatan, Kragilan, Tamanan, Banguntapan, Bantul, Yogyakarta, Indonesia 55191

Phone: +62 (274) 563515, 511830, 379418, 371120
Fax: +62 274 564604

Vol 18, No 2

April 2020

DOI: http://dx.doi.org/10.12928/telkomnika.v18i2

Table of Contents

TELKOMNIKA Telecommunication, Computing, Electronics and Control
ISSN: 1693-6930, e-ISSN: 2302-9293
Universitas Ahmad Dahlan, 4th Campus
Jl. Ringroad Selatan, Kragilan, Tamanan, Banguntapan, Bantul, Yogyakarta, Indonesia 55191
Phone: +62 (274) 563515, 511830, 379418, 371120
Fax: +62 274 564604

Controlling a knee CPM machine using PID and iterative learning control algorithm

Dechrit Maneetham[1], Petrus Sutyasadi[2]
[1]Mechatronics, Rajamangala University of Technology Thanyaburi, Thailand
[2]Mechatronics, Politeknik Mekatronika Sanata Dharma, Indonesia

Article Info

Article history:

Received Jul 18, 2019
Revised Dec 30, 2019
Accepted Feb 14, 2020

Keywords:

CPM
ILC
Learning algorithm
PID
Rehabilitation machine

ABSTRACT

A conventional continuous passive motion (CPM) machine uses simple controller such as On/Off controller. Some better CPMs use PID controller. These kind of CPMs can not distinguish load different due to the different size of the patient leg. This may cause the CPM no longer follow the trajectory or the angle commands. Meanwhile, each patient may have different scenario of therapy from the others. When progress on the patient exists, the range of the flexion may be increased step by step. Therefore, the treatment can be different in term of the range of flexion from time to time. This paper proposes CPM with hybrid proportional integral derivative (PID) and iterative learning controller (ILC). The system has capability in learning the trajectory tracking. Therefore, the CPM will be able to follow any load or trajectory changes applied to it. The more accurate CPM machine can follow the trajectory command, the better its performance for the treatment. The experiment showed that the system was stable due to the PID controller. The tracking performance also improved with the ILC even there exist some disturbances.

Corresponding Author:

Dechrit Maneetham,
Faculty of Technical Education, Mechatronics Engineering,
Rajamangala University of Technology Thanyaburi,
Rangsit-Nakhon Nayok Rd, Khlong Hok, Khlong Luang District, Pathum Thani, Thailand.
Email: dechrit_m@rmutt.ac.th

1. INTRODUCTION

A continuous passive motion (CPM) machine is a mechanism that works according to rehabilitation theory of a continuous and repetitive passive motion [1]. This movement has the purpose in medical practice to recover injured limbs motoric function [2]. the function of a CPM is it may reduce the therapist's workload at the hospital [3]. CPM is expected can be programmed to do a repetitive movement in flexing and bending the patient's muscle.

Some accidents on the knee may cause problem in the anterior cruciate ligament (ACL). The accidents usually make strong impact or hyperextension. In this case, sometimes surgical reconstruction of the ACL must be conducted [4]. ACL injuries are common for some active people [5]. ACL is the most important component for the knee movement. The main function of ACL is to control posterior translation of the femur when the tibia is fixed [6]. Patient with ACL rupture usually need a surgical treatment using tissue autografts or allografts [7] to restore the pivoting spots [8].

After the surgery, early treatment that usually conducted is passive rehabilitation to minimize swelling and pain, but mostly to bring back the range of motion. Passive rehabilitation is moving the limbs while the muscle remains relax. If it is not done by a therapist, it can be done by a CPM machine [9]. According to some researches, by using CPM machine, significant range of motion gain from 7 to 22 degrees has been reported [10–16]. Another reported that during the hospital stay, CPM machine increase the speed of knee flexion recovery [16-19].

Some CPM machine use On/Off control. However, some researchers using proportional integral and derivative (PID) controller, a linear and simple controller to control the CPM machine [20-22]. To handle the non-linear dynamics of the CPM, PID with Neural Network algorithm was also proposed [23]. However, variation of loads may affect the trajectory tracking of the CPM. Iterative learning control (ILC) is a relatively new algorithm that is able to learn and fix a trajectory tracking control problem of a repetitive works [24-26]. CPM machine works in repetitive way. This paper explains the development of a knee CPM machine and its control algorithm using PID-ILC. The goal is having a knee CPM with capability to track the trajectory reference in the presence of various load from the patient’s leg.

2. RESEARCH METHOD

A knee CPM machine was designed and manufactured for the prototype. The machine was actuated by a dc motor. To control the motor, a PID-ILC controller was developed and implemented to the system. The mechanical, electronic, and the controller design are explain in this chapter.

2.1. Mechanical design

The structure is made from stainless steel and aluminium. The drawing of the design is shown in Figure 1. The 3D design of the CPM prototype is shown in Figure 2. The final result of the hardware is shown in Figure 3. The controller and the dc motor driver including the adaptor are put in one box. The the shank support has sponge and covered with vinyl sheet. It also has vinyl strap to hold the patient leg during machine operation. In this case we measure and control the angle of the hip joint (b). The angle was measured from the convertion of the encoder value. Figure 4 shows the hardware test on an adult’s leg. It shows also the ratio or the proportion of the hardware size to an adult’s leg. The straps used to hold the leg so it can follow the CPM movement.

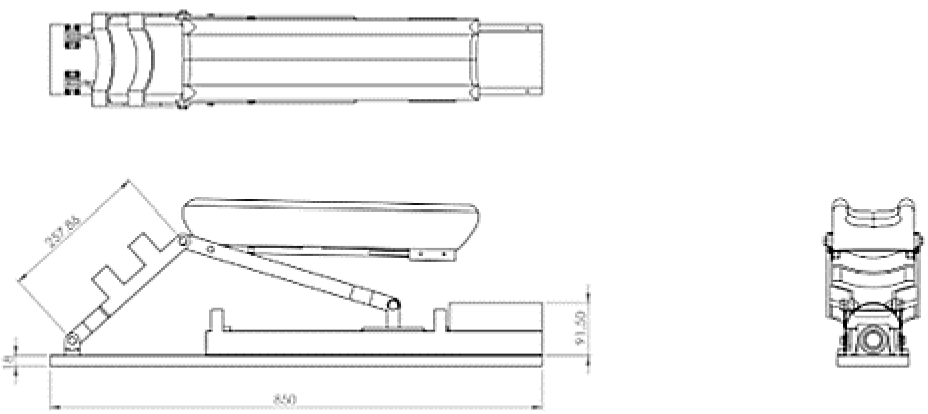
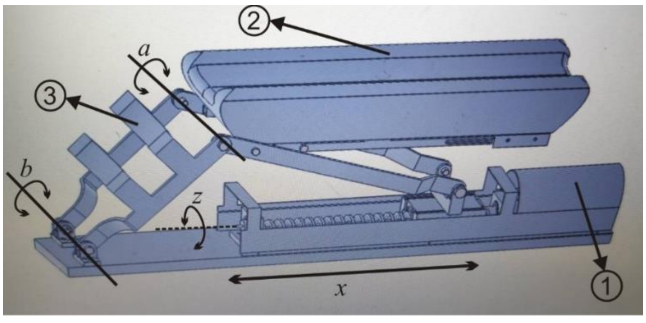


Figure 1. Mechanical design of the CPM (dimension in mm)



a : Knee joint
b : Hip joint
z : Ball screw rotation
x : Slider translation

1 : DC Motor
2 : Shank support
3 : Thight support

Figure 2. There dimensional drawing of the CPM

Figure 3. CPM Prototype

Figure 4. Leg test on the CPM

2.2. Electronic design

The CPM movement is generated by a rotational movement produced by a DC motor. By using a crank slider mechanism, the rotational movement is translated into linear motion. The rotation of the motor is read by using a rotary encoder attached directly to the dc motor shaft at the back. The information of the actual position of the motor is sent to the microcontroller. The position information then will be compared to the trajectory defined and then the error will be manipulated using proportional, integral, and derivative term inside the PID controller. The performance along the trajectory was recorded. The performance in each particular point of the quantized trajectory is compared to the previous one and manipulated using proportional and derivative term inside the ILC controller. The manipulated variable from the ILC was sent and add up to the PID output. The correction signal from the ILC will refine the control signal of the PID. The controller uses Arduino UNO board, and the DC motor driver uses VNH2SP chip that has many advantages such as polarity, over voltage, and over current protection. The detail of the electronic diagram is shown on Figure 5.

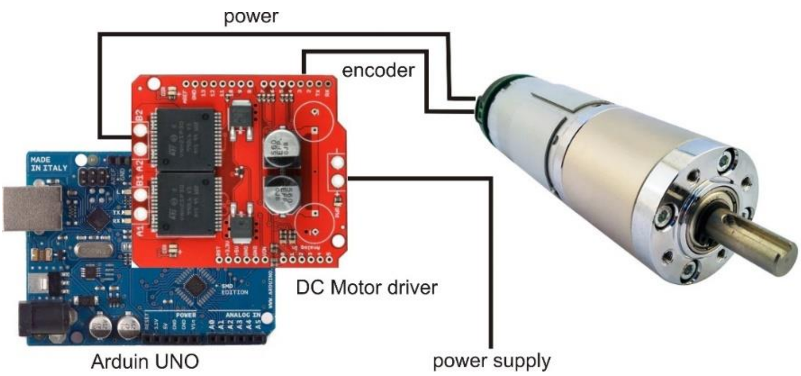


Figure 5. Electronic diagram of the dc motor control

2.3. PID and ILC controller design

Proportional Integral and Derivative (PID) controller was invented in 1910, owned by Elmer Sperry's ship autopilot. The popularity of the controller even grown more since the tuning methods was introduced by Ziegler and Nichols in 1942 [27-28]. PID controller is a controller that calculates the difference between the desired values or Set Point (SP) to the actual value or the output. The difference between SP and output is called the error signal. The error signal then to be processed based on proportional, integral, and derivative terms to get the manipulated variable or the control signal. However, despite of its popularity, even PID controller only consist of three gain to be tuned, it still hard to do. There are still a large number of badly tuned PID controllers on a process plant [29].

Iterative Learning Control (ILC) is a controller that improves the trajectory tracking by leaning from previous task. The previous task means a complete tracking of the whole trajectory from start to end. The conditions that should be fulfilled before using the ILC are:

- It is a repetitive work on a same trajectory.
- The starting and ending position should be the same.
- The system should be stable.

The accuracy of the tracking is improved from one repetition to the next repetition. The system should be a stable system before the ILC is implemented. This is done by the PID controller. In combining PID and ILC then the PID gains should be set to low values but stable. Even the tracking is poor due to the low gain, ILC will adjust the manipulated control signal until the desired trajectory is achieved [30]. Control signal of ILC is determined from

$$u_j = u_{j-1} + k_d \dot{e}_{j-1}(t) + k_p e_{j-1}(t) \quad (1)$$

the hybrid PID-ILC is formed by adding signal from ILC to the PID algorithm. Thus, the controller becomes:

$$u_{PID} = k_p e_j(t) + k_d \dot{e}_j(t) + k_i \int e_j(t)dt + u_j \quad (2)$$

with the variables are:
u_j : ILC control signal,
e_j : error signal,
j : iteration number,
k_p : proportional gain,
k_d : derivative gain,
k_i : integral gain.
The block diagram of the PID-ILC controller is shown in Figure 6.

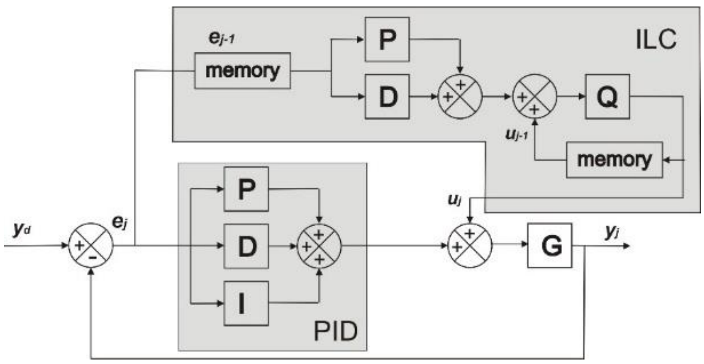


Figure 6. Block diagram of hybrid PID-ILC

3. RESULTS AND ANALYSIS

The CPM was given a triangle wave trajectory input. The variables being controlled are the amplitude of the wave that indicates the angle of the hip joint on the CPM. The PID constant setting is usually done when the CPM has no load on it. Loads may disturb the control system of the CPM. Additional load from patient's leg can change the trajectory tracking response. Theoritically Iterative Learning Control fixes the trajectory tracking within particular time in repetitive way. Figure 7 shows from the experiment that even the PID controller has been tuned properly, but some load applied have changed the trajectory tracking. It did not affect much on the rise time, but the stedy state error was increased significantly. The amplitude reduced 6 degrees. Three degrees less from the maximum position and three degrees from the minimum position.

Figure 8 shows that PID-ILC controller is able to return the trajectory tracking to the trajectory reference. On the first repetition, the PID-ILC produced small overshoot, but later it was able to manage the oscillation to meet the trajectory reference. After four repetitions, the system was able to return to the trajectory reference. Another experiment is with lower PID constant gains set. In the beginning, the system could not track the trajectory reference. However, after several iteration, the system was able to track the trajectory even with initial low PID gain. Figure 9 shows the system response with PID control only and the gains were set low. There are steady state errors. Figure 10 shows combining with ILC, the PID controller after seven iterations the system was able to track the trajectory reference.

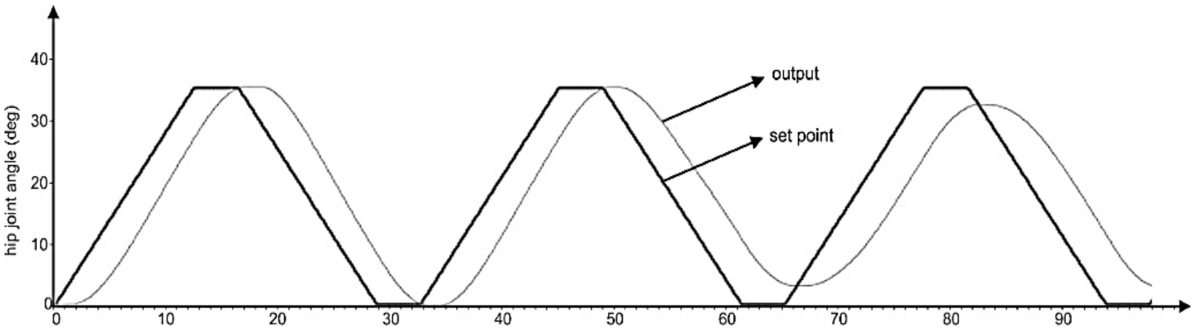
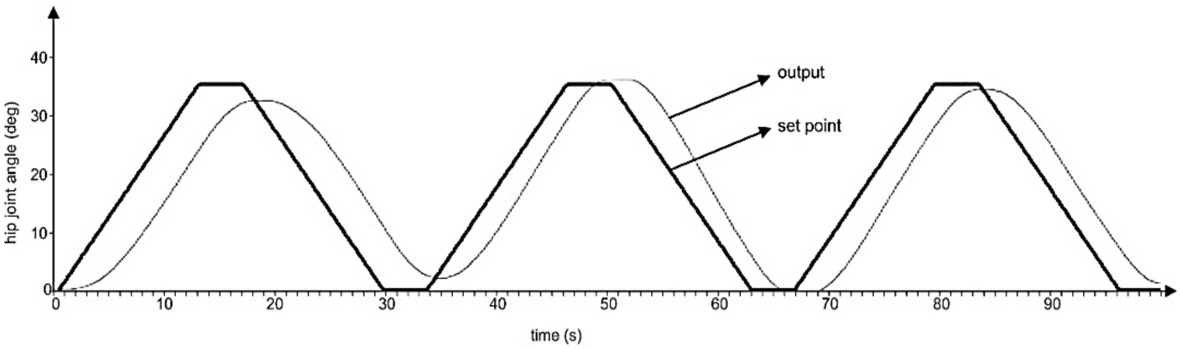
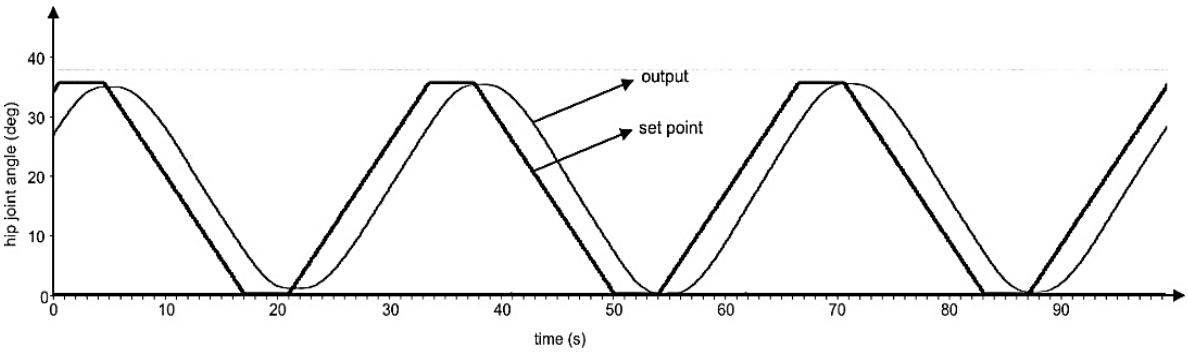


Figure 7. Load changes trajectory tracking of a well tuned PID controller



(a)



(b)

Figure 8. (a) PID-ILC controller tracked back the trajectory reference after disturbance,
(b) after four repetitions PID-ILC perfectly track the trajectory reference

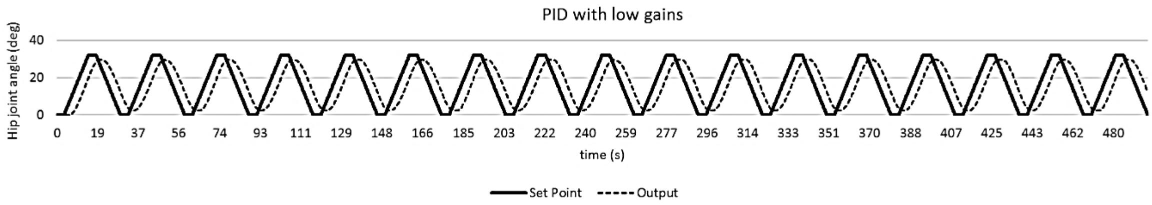


Figure 9. PID controller with low gains

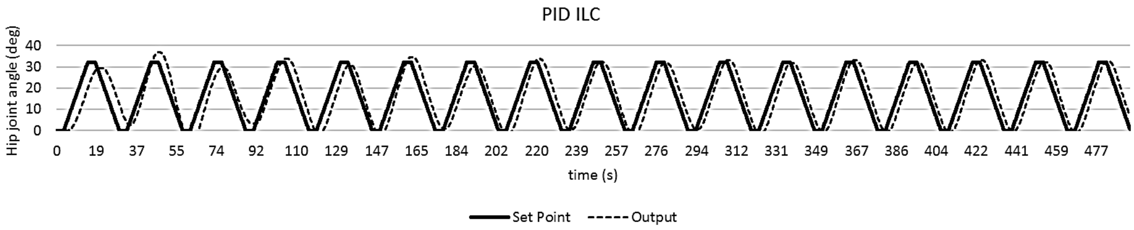


Figure 10. PID-ILC response system

4. CONCLUSION

The CPM machine has been developed and controlled successfully using PID-ILC controller. The mechanical part is able to support the patient leg. All the joints movement are smooth. The proposed hybrid controller successfully controls the system. The system is able to track and follow the trajectory given in the presence of disturbance or load. Well tuned PID controller has 6 degrees steady state error in the appearance of load. However, the PID-ILC able to return the trajectory reference after the 4th repetition. PID-ILC is able to recover the steady state error of a low gain PID controller after 7 repetition. The capability of tracking the trajectory reference will guarantee the system to follow any set of particular patient rehabilitation scenario

REFERENCES

[1] Fu Y., Wang P., Wang S., Liu H., and Zhang F., "Design and development of a portable exoskeleton based CPM machine for rehabilitation of hand injuries," *2007 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, pp. 1476-1481, 2007.

[2] Fu Y., Zhang F., Ma X., Meng Q., "Development of a CPM machine for injured fingers," *Proceedings of the 2005 IEEE Engineering in Medicine and Biologi*, vol. 5, pp. 5017-5020, 2005.

[3] Tangjitsitcharoen S., and Lohasiriwat H., "Redesign of a continuous passive motion machine for total knee replacement therapy," *Journal of Health Research*, vol. 33, no. 2, pp. 106-118, 2019.

[4] Hiemstra L. A., Webber S., and MacDonald P. B., "Knee strength deficits after hamstring tendon and patellar tendon anterior cruciate ligament reconstruction," *Medicine and Science in Sports Medicine*, vol. 32, no. 8, pp.1472-1479, 2000.

[5] Mikkelsen C., Werner S., & Eriksson E., "Close kinetic chain alone compared to combined open and closed kinetic chain exercises for quadriceps strengthening after anterior cruciate ligament reconstruction with respect to return to sports: A prospective matched follow-up study," *Knee Surgery Sports Traumatology Arthroscopy*, vol. 8, no. 6, pp. 337–342, 2000.

[6] Delay B. S., Smolinski R. J., Wind W. M., & Bowman D. S., "Current practices and opinions in ACL reconstruction and rehabilitation," *American Journal of Knee Surgery*, vol. 14, no. 2, pp. 85–91, 2001.

[7] Woo S. L. Y., Wu C., Dede O., Vercillo F., and Noorani S., "Biomechanics and anterior cruciate ligament reconstruction," *Journal of Orthopaedic Surgery and Research*, vol. 1, no. 2, September 2006.

[8] Lee D. Y. H., Karim S. A., Chang H. C., "Return to sports after anterior cruciate ligament reconstruction – a review of patients with minimum 5-year follow-up," *Annals of the Academy of Medicine, Singapore*, vol. 37, no. 4, pp. 273-278, 2008.

[9] Rashid M. R., Ahmad I. N., Haron R., and Adnan R., "Treatment effectiveness of continuous passive motion machine during post-operative treatment of anterior cruciate ligament patients," *2012 IEEE Symposium on Humanities, Science and Engineering Research*, pp. 469-473, 2012.

[10] McInnes J., Larson M. G., Daltroy L. H., et al., "A controlled evaluation of continuous passive motion in patients undergoing total knee arthroplasty," *JAMA*, vol. 268, no. 11, pp. 1423– 1428, September 1992.

[11] Pope R. O., Corcoran S., McCaul K., Howie D. W., "Continuous passive motion after primary total knee arthroplasty: does it offer any benefits?" *The Bone & Joint Journal*, vol. 79, no. 6, pp. 914– 917, 1997.

[12] Shih K. Z., Liu T. K., "The role of continuous passive motion following total knee arthroplasty," *Journal of the Formosan Medical Association*, vol, 89, no. 12, pp. 1077– 1080, 1990.

[13] Ververeli P. A., Sutton D. C., Hearn S. L., et al., "Continuous passive motion after total knee arthroplasty: analysis of cost and benefits," *Clinical Orthopaedics and Related Research*, no. 321, pp. 208– 215, 1995.

[14] Wasilewski S. A., Woods L. C., Torgerson W. R. J., Healy W. L., "Value of continuous passive motion in total knee arthroplasty," *Orthopedics*, vol. 13, no. 3, pp. 291– 295, 1990.

[15] Harms M., Engstrom B., "Continuous passive motion as an adjunct to treatment in the physiotherapy management of total knee arthroplasty patient," *Physiotherapy*, vol. 77, no. 4, pp. 301– 307, 1991.

[16] Johnson D. P., Eastwood D. M., "Beneficial effects of continuous passive motion after total condylar knee arthroplasty," *Annals of the Royal College of Surgeons of England*, vol. 74, no. 6, pp. 412-416, 1992.

[17] Romness D. W., Rand J. A., "The role of continuous passive motion following total knee arthroplasty," *Clinical Orthopaedics and Related Research*, no. 226, pp. 34– 37, 1988.

[18] Goletz T. H., Henry J. H., "Continuous passive motion after total knee arthroplasty," *Southern Medical journal*, vol. 79, no. 9, pp. 1116–1120, 1986.

[19] Vince K. G., Kelly M. A., Beck J., Insall J. N., "Continuous passive motion after total knee arthroplasty," *The Journal of Arthroplasty*, vol. 2, no.4, pp. 281–284, 1987.

[20] Uetsuji S., Kingsuvangul N., Boonyasurakul B., and Charoensuk W., "Hand exoskeleton for continuous passive motion postoperative rehabilitation," *2017 10th Biomedical Engineering International Conference (BMEiCON)*, pp. 1-5, 2017.

[21] Eski I., Kirnap A., and Kirnap M., "PID controller design for human elbow therapy," *International Journal of Applied Mathematics, Electronics and Computers*, no. 4, pp. 282–285, 2016.

[22] Ortega A. B., Becerra F. A. G., Valdés L. G. V., dan Arcega R. O. D., "A generalized proportional integral controller for an ankle rehabilitation machine based on an XY table," *2013 International Conference on Mechatronics, Electronics and Automotive Engineering*, Morelos, pp. 152-157, 2013.

[23] Tu Diep Cong Thand., "Control Novel Model of Knee CPM Device, science & technology development," *Science and Technology Develogment*, vol 12, no. 4, pp 18-29, 2009.

[24] S. Arimoto, S. Kawamura, and F. Miyazaki, "Bettering operation of robots by learning," *Journal of Robotic Systems*, vol. 1, no. 2, pp.123-140, 1984.

[25] Ibid, "Bettering operation of dynamic systems by learning: A new control theory for servomechanism or mechatronics systems," *The 23rd IEEE Conference on Decision and Control*, pp. 1064-1069, 1984.

[26] S. Kawamura, F. hliyazaki and S. Arimoto, "Iterative learning control for robotic systems," *2009 IEEE International Conference on Control and Automation, Christchurch*, pp. 1092-1097, 2009.

[27] Ziegler Z. G., and Nichols N. B., "Optimum settings for automatic controllers," *Trans. ASME*, vol. 64, pp. 759–768, 1942.

[28] Ang K. H., Chong G., and Li Y., "PID Control System Analysis, Design, and Technology," *IEEE Transactions on Control Systems Technology*, vol. 13, no. 4, pp. 559-576, 2005.

[29] Skogestad S., "Simple analytic rules for model reduction and PID controller tuning," *Journal of Process Control* vol. 13, no. 4, pp. 291–309, 2003.

[30] Sutyasadi P., and Parnichkun M., "Trotting control of a quadruped robot using PID-ILC," in *IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society*, pp. 004400-004405, 2015.