IECON2015 - Yokohama

41st Annual Conference of the IEEE Industrial Electronics Society

November 9 – 12, 2015

Pacifico Yokohama, Yokohama, Japan

PROGRAM BOOK

Sponsored by

IEEE

1951-2011 ies 60th anniversary

IEEE Industrial Electronics Society (IES)

IECON2015-Yokohama

Monday 9th of November, 2015

	Room 1: 301	Room 2: 302	Room 3: 303	Room 4: 304	Room 5: 311	Room 6: 312	Room 7: 313	Room 8: 314	Room 9: 315	Room 10: 411	Room 11: 412	Room 12: 413	Room 13: 414	Room 14: 415	Room 15: 416	Room 16: 417	Room 17: 418	Room 18: 419
09:00-10:00	Registration																	
10:00-12:00	TS-1		TS-2	TS-3	TS-4	TS-5	TS-6	TS-7	TS-8	TS-9	TS-10	TS-11	TS-12	TS-13	TS-14	TS-15	TS-16	TS-17
12:00-13:20 (Lunch)	Unavailable		*	*	TC20	TC04	TC06	TC08	TC12	*	*	*	*	*	*	*	*	*
13:20-15:20	Industry Forum		T03	T05	T09	T11	T15	T13	T07	T01	TS-18	TS-19	TS-20	TS-21	TS-22	TS-23	TS-24	TS-25
15:20-15:40	Coffee Break																	
15:40-17:40	Industry Forum		T06	T10	T04	*	*	T08	T14	*	TS-26	TS-27	TS-28	TS-29	TS-30	TS-31	TS-32	TS-33
18:00-20:00	Welcome Reception (Room 501+502, Pacifico Yokohama)																	

Tuesday 10th of November, 2015

	Room 1: 301	Room 2: 302	Room 3: 303	Room 4: 304	Room 5: 311	Room 6: 312	Room 7: 313	Room 8: 314	Room 9: 315	Room 10: 411	Room 11: 412	Room 12: 413	Room 13: 414	Room 14: 415	Room 15: 416	Room 16: 417	Room 17: 418	Room 18: 419
08:45-09:00	Opening Session (Room 1+Room 2)																	
09:00-10:00	Plenary Session 1 (Room 1+Room 2)																	
10:00-10:30	Coffee Break																	
10:30-12:30			TS-34	TS-35	TS-36	TS-37	TS-38	TS-39	TS-40	TS-41	TS-42	TS-43	TS-44	TS-45	TS-46	TS-47	TS-48	TS-49
12:30-13:50 (Lunch)	*	*	IEEE Transactions on Industrial Electronics: Farewell / Welcome meeting	*	*	*	*	*	*	TC02	TC03	TC05	TC11	TC13	TC14	TC15	TC21	TC23
13:50-15:30	TS-50	TS-51	TS-52	TS-53	TS-54	TS-55	TS-56	TS-57	TS-58	TS-59	TS-60	TS-61	TS-62	TS-63	TS-64	TS-65	TS-66	TS-67
15:30-15:50	Coffee Break																	
15:50-17:30	TS-68	TS-69	TS-70	TS-71	TS-72	TS-73	TS-74	TS-75	TS-76	TS-77	*	TS-79	TS-80	TS-81	TS-82	TS-83	TS-84	TS-85

Student Forum (Harbor Lounge B)
10:30-12:00
Student Tutorial and Industry Link

13:00-16:45
Student Forum I, II
18:30-20:00
Student Banquet

Wednesday 11th of November, 2015

	Room 1: 301	Room 2: 302	Room 3: 303	Room 4: 304	Room 5: 311	Room 6: 312	Room 7: 313	Room 8: 314	Room 9: 315	Room 10: 411	Room 11: 412	Room 12: 413	Room 13: 414	Room 14: 415	Room 15: 416	Room 16: 417	Room 17: 418	Room 18: 419
09:00-10:00	Plenary Session 2 (Room 1+Room 2)																	
10:00-10:30	2015 IES Award (Coffee Break)																	
10:30-11:30	Plenary Session 3 (Room 1+Room 2)																	
11:30-13:00 (Lunch)	Unavailable		IES Forum on Quality Publication	*	*	*	*	*	*	TC01	TC07	TC09	TC10	TC16	TC17	TC18	TC19	TC22
13:00-15:00	TS-86	TS-87	TS-88	TS-89	TS-90	TS-91	TS-92	TS-93	TS-94	TS-95	TS-96	TS-97	TS-98	TS-99	TS-100	TS-101	TS-102	TS-103
15:00-15:20	Coffee Break																	
15:20-17:20	TS-104	TS-105	TS-106	TS-107	TS-108	TS-109	TS-110	TS-111	TS-112	TS-113	TS-114	TS-115	TS-116	TS-117	TS-118	TS-119	TS-120	TS-121
18:30-21:00	Banquet (Ground Ballroom "HOH-SHOH" located at the 3rd floor, banquet center, Yokohama Royal Park Hotel)																	

Thursday 12th of November, 2015

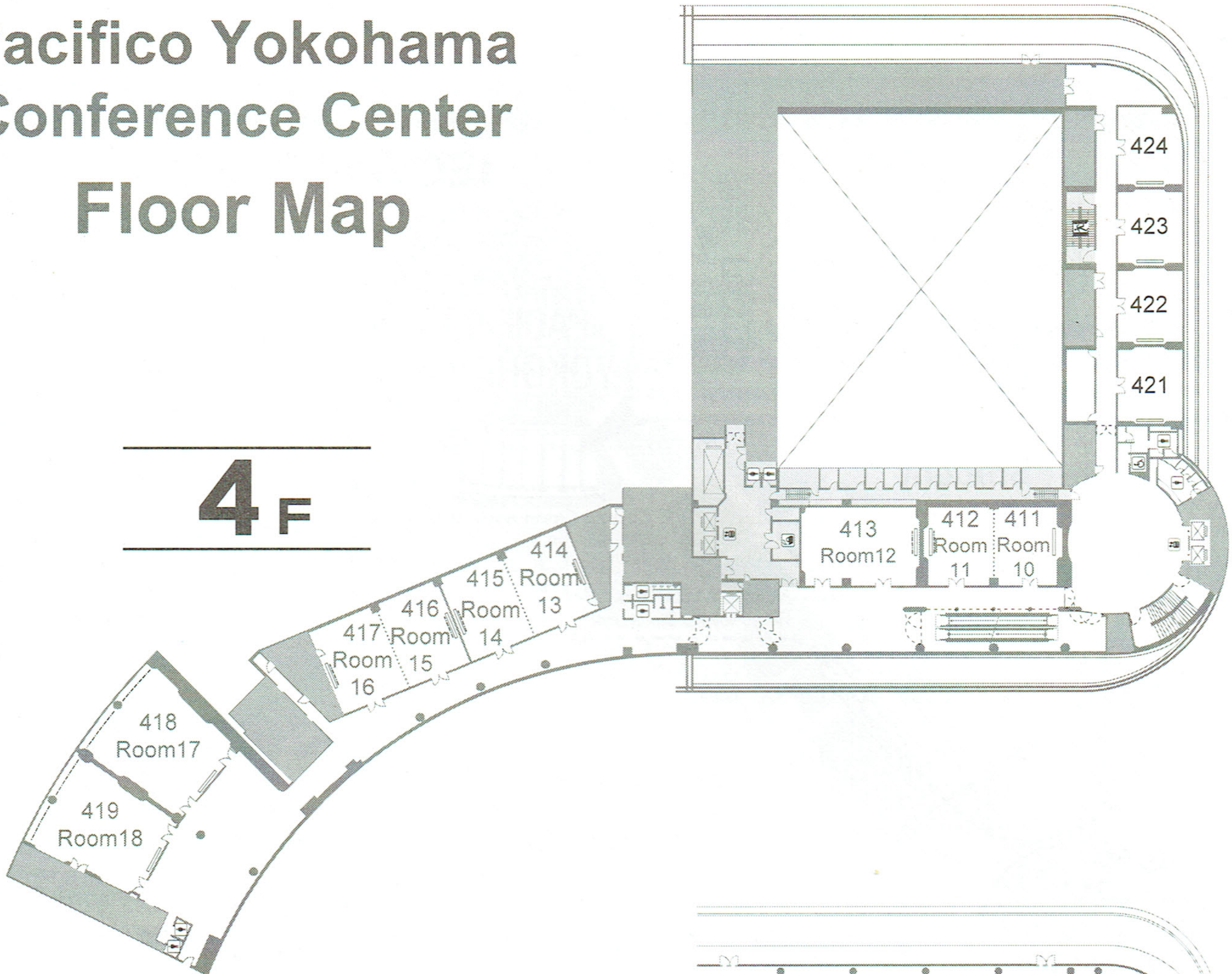
	Room 1: 301	Room 2: 302	Room 3: 303	Room 4: 304	Room 5: 311	Room 6: 312	Room 7: 313	Room 8: 314	Room 9: 315	Room 10: 411	Room 11: 412	Room 12: 413	Room 13: 414	Room 14: 415	Room 15: 416	Room 16: 417	Room 17: 418	Room 18: 419
09:00-10:40	TS-122	TS-123	TS-124	TS-125	TS-126	TS-127	TS-128	TS-129	TS-130	AdCom Meeting	AdCom Meeting	AdCom Meeting	TS-131	TS-132	TS-133	TS-134	TS-135	*
10:40-11:00	Coffee Break																	
11:00-12:40	TS-137	TS-138	TS-139	TS-140	TS-141	*	*	TS-144	TS-145	AdCom Meeting	AdCom Meeting	AdCom Meeting	TS-146	TS-147	TS-148	TS-149	TS-150	TS-151
12:40-14:00 (Lunch)										AdCom Lunch								
14:00-16:00	TS-152	TS-153	TS-154	TS-155	TS-156	TS-157	TS-158	TS-159	TS-160	AdCom Meeting	AdCom Meeting	AdCom Meeting	TS-161	TS-162	TS-163	TS-164	TS-165	TS-166
16:00-16:20	Coffee Break																	
16:20-18:00	TS-167	TS-168	TS-169	TS-170	TS-171	TS-172	*	TS-174	*	AdCom Meeting	AdCom Meeting	AdCom Meeting	*	TS-177	*	TS-179	TS-180	TS-181
19:00-22:00	AdCom Dinner																	

Friday 13th of November, 2015

	Harbor Lounge A/B
8:00-12:00	AdCom Meeting
12:00-13:00	AdCom Lunch
13:00-17:00	AdCom Meeting
18:00-21:00	Post-AdCom Dinner

Pacifico Yokohama Conference Center
Floor Map

4F



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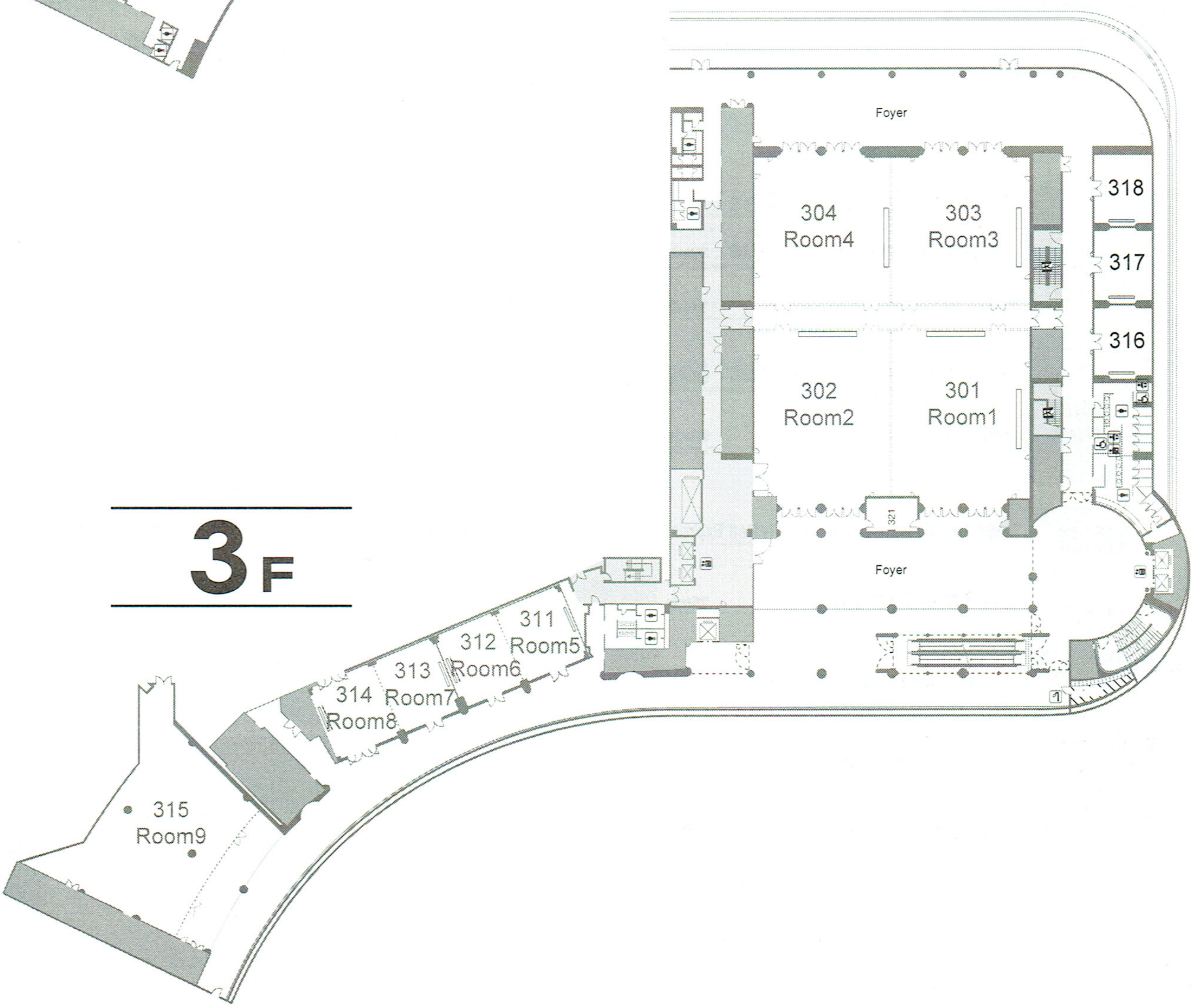
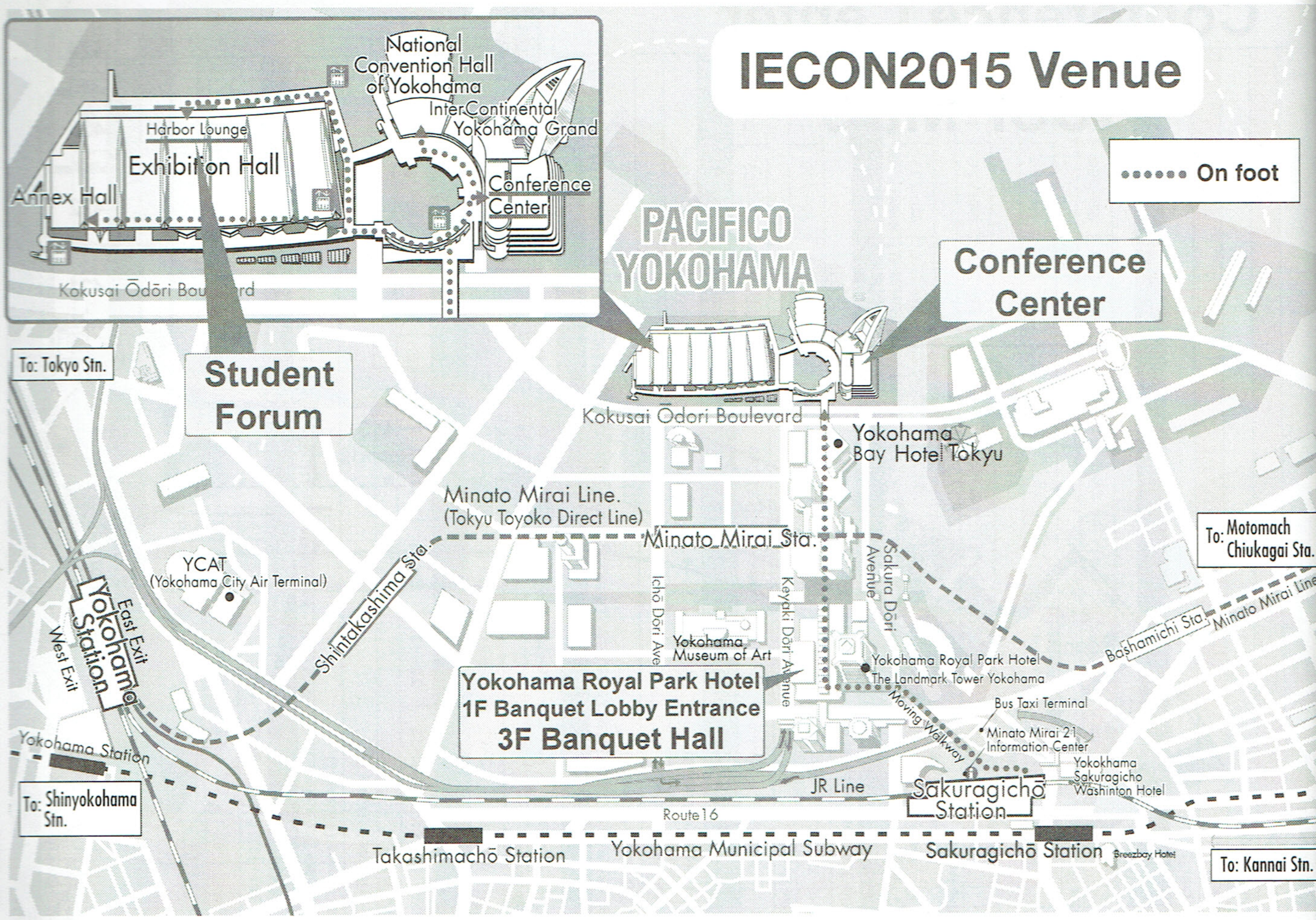
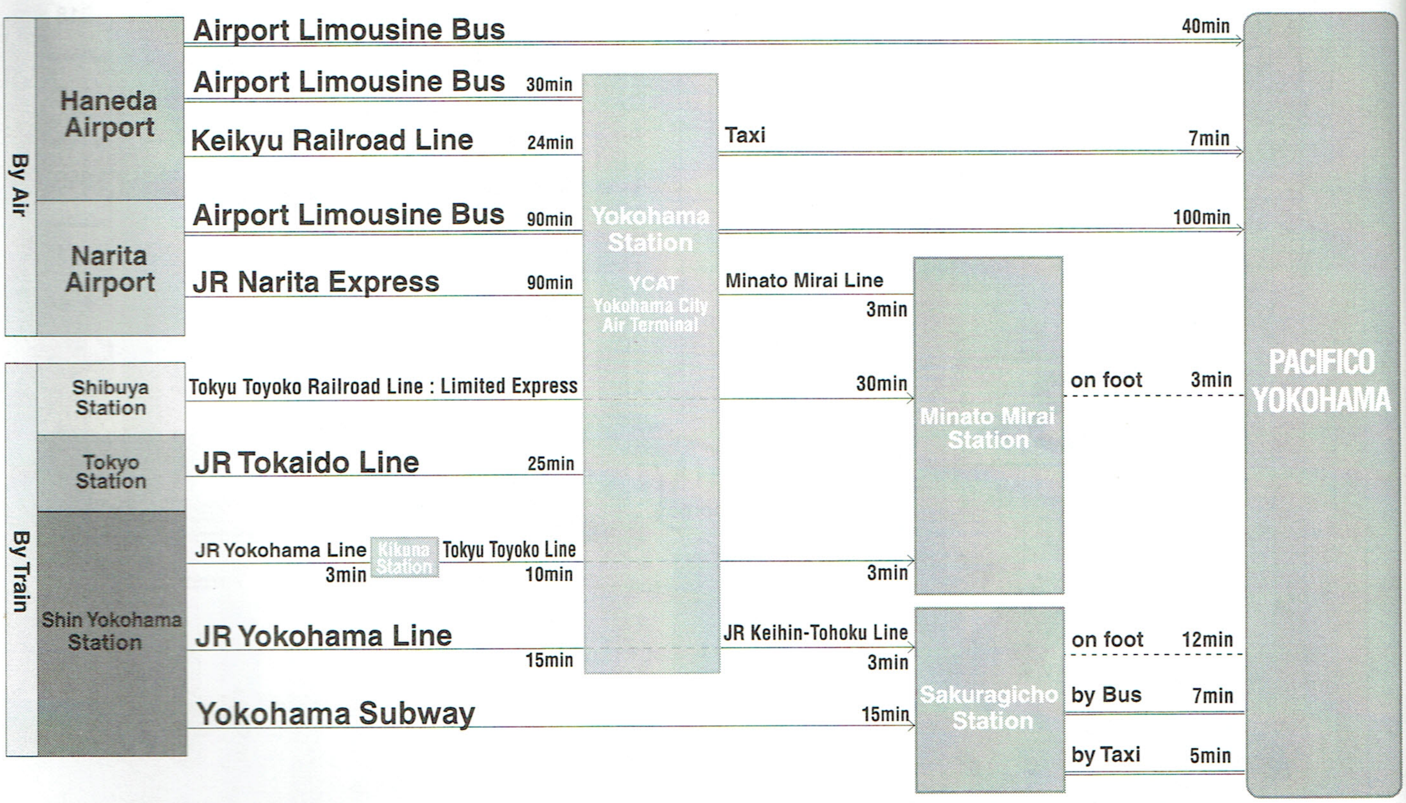



IECON2015 Venue
On foot
PACIFICO YOKOHAMA
Conference Center
Student Forum
National Convention Hall of Yokohama
InterContinental Yokohama Grand
Harbor Lounge
Exhibition Hall
Annex Hall
Conference Center
Kokusai Ōdōri Boulevard
To: Tokyo Stn.
Kokusai Ōdori Boulevard
Yokohama Bay Hotel Tokyu
Minato Mirai Line.
(Tokyu Toyoko Direct Line)
Minato Mirai Sta.
To: Motomach Chiukagai Sta.
YCAT
(Yokohama City Air Terminal)
Shintakashima Sta.
Yokohama Station
East Exit
West Exit
Ichō Dōri Ave
Keyaki Dōri Avenue
Sakura Dōri Avenue
Yokohama Museum of Art
Yokohama Royal Park Hotel
1F Banquet Lobby Entrance
3F Banquet Hall
Yokohama Royal Park Hotel
The Landmark Tower Yokohama
Moving Walkway
Bashamichi Sta.
Minato Mirai Line
Bus Taxi Terminal
Minato Mirai 21 Information Center
Yokohama Sakuragicho Washinton Hotel
Yokohama Station
To: Shinyokohama Stn.
JR Line
Sakuragichō Station
Route16
Takashimachō Station
Yokohama Municipal Subway
Sakuragichō Station
To: Kannai Stn.


By Air
Haneda Airport
Airport Limousine Bus
40min
Airport Limousine Bus
30min
Keikyu Railroad Line
24min
Taxi
7min
Narita Airport
Airport Limousine Bus
90min
100min
JR Narita Express
90min
Yokohama Station
YCAT Yokohama City Air Terminal
Minato Mirai Line
3min
By Train
Shibuya Station
Tokyu Toyoko Railroad Line : Limited Express
30min
on foot
3min
Minato Mirai Station
PACIFICO YOKOHAMA
Tokyo Station
JR Tokaido Line
25min
Shin Yokohama Station
JR Yokohama Line
3min
Kikuna Station
Tokyu Toyoko Line
10min
3min
JR Yokohama Line
15min
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3min
on foot
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by Bus
7min
Yokohama Subway
15min
by Taxi
5min

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The 41st Annual Conference of the IEEE Industrial Electronics Society (IECON2015)

IECON 2015 is the 41st Annual Conference of the IEEE Industrial Electronics Society, focusing on industrial and manufacturing theory and applications of electronics, controls, communications, instrumentation and computational intelligence. The objectives of the conference are to provide high quality research and professional interactions for the advancement of science, technology, and fellowship.

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Welcome Message from the IECON2015 General Chairs

On behalf of the Organizing Committee of IECON2015, it is with great pleasure and honor we welcome all the participating delegates from 53 countries to take part in the 41st Annual Conference of the IEEE Industrial Electronics Society (IECON) that is being held in Yokohama in the prefecture of Kanagawa, Japan, form November 9th to November 12th, 2015. Throughout the past 41 years, IECON has excelled in showcasing creativity, in providing an ideal environment for technical exchange and networking, and most importantly in emphasizing the applied nature of the industrial electronics/informatics over a wide range of industries. IECON2015 is also focusing on industrial and manufacturing theory and applications of electronics, controls, communications, instrumentation and computational intelligence.

Yokohama is the first harbor city introduced to the world as the entrance to Japan. Since the time its port was opened, Yokohama has been vigorously acquiring new cultures and information from foreign countries and introducing to Japan our country's first-time-ever things from food to a wide range of cultures, which entitles Yokohama as the birthplace of Japan's modern culture. In Minato Mirai 21, which is the conference area, is the popular tourist spots in Yokohama. Yokohama Landmark Tower has 296 meter skyscraper with a shopping complex. Yokohama Red Brick Warehouse is a complex building where you can enjoy shopping and dining of every kind.

IECON 2015 had 1250 papers submitted from 47 countries. After the review process, IECON2015 has 932 high quality accepted papers, which includes 14 Student Forum papers, 312 Special Session papers and 606 Technical Track Session papers. IECON2015 has three plenary sessions based on the highly reputed speakers. Moreover, IECON2015 has the timely and interesting Industry Forum based on eight industrial leaders having highly rich experience.

We would like to thank all authors and participants who have contributed to make this event a great success. Finally, we would like to specially thank to all of the volunteers who have worked very hard at all levels, those who participated in the review process, the special session organizers, the technical tracks chairs, the technical committees members, the industry forum organizers, the student forum organizers and the local and international organizing committees. Moreover, we would like to thank to all IES officers who helped us in promoting Yokohama as the host of IECON2015.

Prof. Kiyoshi Ohishi
Nagaoka University of Technology

Prof. Hideki Hashimoto
Chuo University

IEEE IECON2015 General Co-Chairs

Welcome Message from the IECON2015 Technical Program Chairs

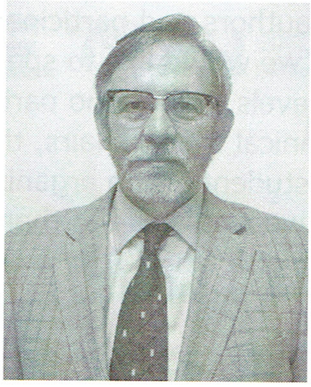
On behalf of the Technical Program Committee, it is our great pleasure and honor to welcome you to Yokohama for the 41st Annual Conference of the IEEE Industrial Electronics Society (IECON2015). The main objective of IECON2015-Yokohama is to provide a forum for researchers, educators and engineers in the general field of industrial electronics to disseminate their latest research results and work up technical interests in the future research directions of the related fields.

A converge of IECON is very wide and the IECON2015 is no exception. We have 17 regular tracks covering various fields and 47 call for special sessions. The program also includes 15 tutorials from experts. All 1230 submissions were thoroughly reviewed and only 918 high quality papers were included in the final program. Presentations at IECON2015-Yokohama are organized in 18 parallel tracks, for a total of 173 oral sessions, taking place during the four conference days. We have the fortune to be able to invite some distinguished speakers to deliver plenary talks. We would like to thank all the members of authors, plenary speakers and attendees for their support and participation.

We wish to express our most sincere appreciation and thanks to all the individuals who have contributed to the organization of this conference. Our special thanks are extended to our colleagues in the Program Committee for their review of all the submitted papers, which is important for the success of this conference, and the Track Chairs and the Special Session Chairs for their attractive proposal of sessions. We also extend our great thanks to the Local Arrangement Committee who have spent their time for ensuring the success of this conference.

We hope that you will have fruitful conference and enjoyable stay in Yokohama, Japan.

Prof. Toshiyuki Murakami
Keio University



Prof. Leopoldo G. Franquelo
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Prof. Mo-Yuen Chow
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Yasuharu Kunii, Japan
Milos Manic, USA

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Ryogo Kubo, Japan
Lucia Lo Bello, Italy
Valeriy Vyatkin, Finland

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Thilo Sauter, Austria
Stamatis Karnouskos, Germany

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Kanghyun Jo, South Korea

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Satoshi Suzuki, Japan
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Energy Storage Systems
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Chengbin Ma, China
Habiballah Rahimi-Eichi, USA
Sousuke Nakamura, Japan

Special Session Organizers

SS1 - Big Data Analytics for Industrial Informatics
Elizabeth Chang, Australia
Paulo Leitao, Portugal
Tharam Dillon, Australia
Farookh Khadeer Hussain, Australia

SS2 - (canceled)

SS3 - (canceled)

SS4 - (canceled)

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Tomonori Kato, Japan
Kenji Tahara, Japan

SS6 - Wireless Power Transfer
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Chunhua Liu, Hong Kong

SS7 - Advancing Electric Vehicle Technologies
Chunhua Liu, Hong Kong
Zhen Zhang, Hong Kong

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Claudio Carretero, Spain

SS9 - Biomimetics and Intelligent Robotics
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Keigo Watanabe, Japan
Fusaomi Nagata, Japan

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Sebastian Rohjans, Germany

SS11 - Real-time Simulation and Hardware-in-the-Loop Validation Methods for Power and Energy Systems
Georg Lauss, Austria
Thomas Strasser, Austria

SS12 - Smart Sensors for the Future "Internet of Things"
Zhichao Tan, China
Stoyan Nihtianov, Netherlands
Ridha Ben-Mrad, Canada
Antonio Luque, Spain

SS13 - Signal and Image Processing and Pattern Recognition Techniques for Electric Machine and Power Electronics Fault Diagnosis and Prognosis
Jose Antonino-Daviu, Spain
Hubert Razik, France

SS14 - New methodologies in electrical and electronic engineering education
Jose Antonino-Daviu, Spain
Larisa Dunai Dunai, Spain

SS15 - Fault Detection, Diagnostics and Prognostics in Electromechanical Devices
Omid Geramifard, Singapore
Le Tung, Singapore
Jian-Xin Xu, Singapore

SS16 - Multiphase Electric Machines for Generation and Motor Applications
Emil Levi, UK
Federico Barrero, Spain

SS17 - Biomedical Applications of Industrial Electronics
Carlo Cecati, Italy
Toshio Fukuda, Japan
Óscar Lucía, Spain

SS18 - Control and Filtering for Distributed Networked Systems
Qing-Long Han, Australia
Chen Peng, China

SS19 - Advanced Control of Robotic Systems
Michael Ruderman, Japan
Makoto Iwasaki, Japan

SS20 - (canceled)

SS21 - Multilevel Converters for Renewable Energy Systems
Hadi Y. Kanaan, Lebanon
Kamal Al-Haddad, Canada

SS22 - Advanced Power Electronics for Power Quality Improvement in Distributed Systems
Hadi Y. Kanaan, Lebanon
Kamal Al-Haddad, Canada

SS23 - Vision Sensing and Data Processing for Human Assistive Systems
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Toshiyuki Murakami, Japan

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Patrick Wheeler, UK
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Makoto Iwasaki, Japan
Roberto Oboe, Italy
Toshiaki Tsuji, Japan

SS29 - Engineering Paradigms for Automated Facilities
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Tobias Jäger, Germany
Paulo Leitão, Portugal

SS30 - Recent Developments on Time-Delay Systems and Their Applications
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Yutaka Uchimura, Japan

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T. W. Ching, Macau

SS32 - Renewable Energy Harvesting Technique for Future Energy Systems
Wenlong Li, Hong Kong
T. W. Ching, Macau

SS33 - Intelligent Robotic Control and Motion Planning
Xu Jianxin, Singapore
Ren Qinyuan, Singapore

SS34 - Vehicle Intelligence for Proactive Assistance
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Takashi Bando, Japan
Tadahiro Taniguchi, Japan

SS35 - Bio-signal and Multimedia Signal Processing
Nozomu Hamada, Malaysia
Yasue Mitsukura, Japan

SS36 - (canceled)

SS37 - Human Support and Monitoring Technology on Human Factors
Kang-Hyun JO, South Korea
Hiroshi HASHIMOTO, Japan
Sho YOKOTA, Japan
Satoshi SUZUKI, Japan

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Kyougnchul Kong, South Korea
Hiroshi Fujimoto, Japan

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Paulo Leitão, Portugal
João Martins, Portugal

SS40 - Wireless and Cloud Systems for Industrial Sensing Applications
Mikael Gidlund, Sweden
Kim Fung Tsang, Hong Kong
Gerhard P. Hancke, Hong Kong

SS41 - Real-World Haptics Based on Motion Control Technology
Seiichiro Katsura, Japan
Kiyoshi Ohishi, Japan
Yasutaka Fujimoto, Japan

SS42 - Fault Diagnosis and Fault Tolerance in Power Electronics and Drives
Chiara Boccaletti, Italy
António João Marques Cardoso, Portugal

SS43 - Building Automation –Solving the Complexity Challenges
Jan Haase, Germany
Gerhard Zucker, Austria

SS44 - Static and Dynamic Wireless Charging for Electric Transportation
Giuseppe Buja, Italy
Akshay Kumar Rathore, Singapore
Kishore Naik Mude, Italy

SS45 - Resonant Power Converters Topologies, Control Techniques and Applications
Maria Teresa Outeiro, Portugal
Giuseppe Buja, Italy

SS46 - Information and Communication Technology for Smart Energy Application

Palensky Peter, Netherlands
Jan Haase, Germany
Hiroaki Nishi, Japan

SS47 - Nonlinear Control Techniques for Power System and Renewable Energy Applications

Ahmed Al-Durra, United Arab Emirates
S.M. Muyeen, United Arab Emirates
M. E. H. Benbouzid, France

TROTTING CONTROL OF A QUADRUPED ROBOT USING PID-ILC

Petrus Sutyasadi
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***Abstract*—This paper presents the development of a quadruped robot and introduces its trotting control algorithm. Dynamic control of a four-leg robot is not an easy task. Several attentions are required especially on the stability aspect. During trotting, the quadruped robot is supported only by its two diagonal legs. In this stage, the robot is unstable and easy to fall over. The instability becomes even worse with the presence of external and internal disturbances caused by the movement of legs or body of the robot. The stability of the quadruped robot is achieved by controlling its center of gravity (CoG) trajectory during trotting. The joint trajectory is controlled using hybrid Proportional Integral Derivative – Iterative Learning Control (PID-ILC). The CoG position is controlled based on the trunk attitude. The experimental results reveal that PID-ILC needs only 10 iterations before it can follow the desired path. Trunk attitude is improved three times better by having small pitch and roll angle less than ±3.7 degree.**

***Keywords*— quadruped robot; trot gait; iterative learning**

I. INTRODUCTION

Quadruped robot is a four-leg robot. It uses legs for locomotion instead of wheels. Research in leg-locomotion of mobile robot is still an interesting topic because of its unique advantages over the wheel robot [1]. Leg robot has good mobility in avoiding obstacles as well as during surmounting [2]. In natural terrain where there are many non-continue paths, leg robot has superior locomotion performance than the wheel robot.

However, trajectory tracking and stability control of leg robot is still a challenge topic. A quadruped robot has static stability because of its four supporting legs [3]. As long as the center of gravity is inside robot's supporting polygon formed by its legs, the robot is statically stable. However, motion with static balancing is considerably slow. To get faster motion the robot has to use dynamic gait pattern; such as trot, gallop, or bound. Dynamic gait pattern motion requires complicated dynamic control of the robot and good mechanical design. During dynamic gait pattern motion, the robot is more sensitive to disturbance in comparison to static balancing motion.

II. KIEMATIC OF A QUADRUPED ROBOT

A 12-DOF quadruped robot is developed at AIT. Each leg contains 3 degrees of freedom as shown in Figure 1. Based on the reference frames embedded at the joints of the robot, the D-H parameters are given in Table1:

TABLE I. D-H PARAMETERS OF AIT QUADRUPED ROBOT

Parameters	*links*		
a_i	a_1	a_2	a_3
α_i	$\pi/2$	0	0
d_i	0	0	0
θ_i	θ_1	θ_2	θ_3

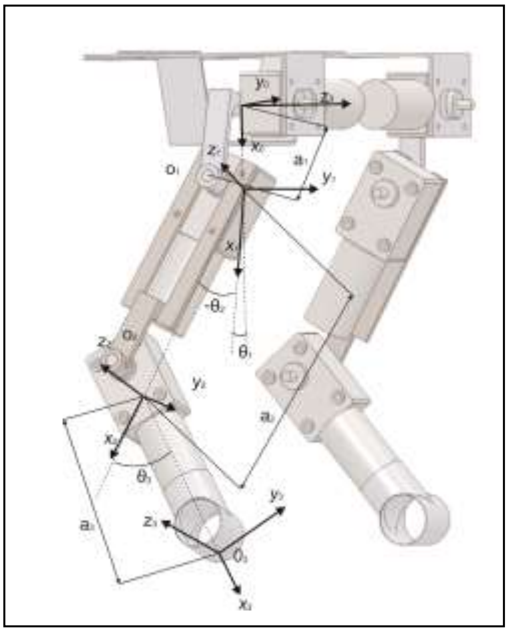

Fig. 1. D-H parameters of a leg of AIT quadruped robot

The homogenous transformation matrices of the quadruped robot are obtained.

$$
{}^{0}A_1 = \begin{pmatrix} \cos\theta_1 & 0 & \sin\theta_1 & a_1\cos\theta_1 \\ \sin\theta_1 & 0 & -\cos\theta_1 & a_1\sin\theta_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{1}
$$

$$ {}^{1}A_2 = \begin{pmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & a_2\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & a_2\sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (2) $$

$$ {}^{2}A_3 = \begin{pmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & a_3\cos\theta_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & a_3\sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (3) $$

Therefore, the homogeneous transformation matrix that is used to transform coordinate of the foot reference frame to the shoulder reference frame can be represented by:

$$ {}^{0}A_3 = {}^{0}A_1\,{}^{1}A_2\,{}^{2}A_3 = \begin{pmatrix} R_{3x3} & d_{3x1} \\ 0_{1x3} & 1 \end{pmatrix} $$

$$ = \begin{pmatrix} \cos\theta_1\cos(\theta_2+\theta_3) & -\sin(\theta_2+\theta_3)\cos\theta_1 & \sin\theta_1 & \cos\theta_1\left(a_3\cos(\theta_2+\theta_3)+a_2\cos\theta_2+a_1\right) \\ \sin\theta_1\cos(\theta_2+\theta_3) & -\sin(\theta_2+\theta_3)\cos\theta_1 & -\cos\theta_1 & \sin\theta_1\left(a_3\cos(\theta_2+\theta_3)+a_2\cos\theta_2+a_1\right) \\ \sin(\theta_2+\theta_3) & \cos(\theta_2+\theta_3) & 0 & a_3\sin(\theta_2+\theta_3)+a_2\sin\theta_2 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (4) $$

Where $d = (x,y,z)^T$ is the foot position vector.

$$ x = \cos\theta_1\left(a_3\cos(\theta_2+\theta_3)+a_2\cos\theta_2+a_1\right) \quad (5) $$

$$ y = \sin\theta_1\left(a_3\cos(\theta_2+\theta_3)+a_2\cos\theta_2+a_1\right) \quad (6) $$

$$ z = a_3\sin(\theta_2+\theta_3)+a_2\sin\theta_2 \quad (7) $$

In order to get the joint angles from a foot position, an inverse kinematics of the quadruped robot is analyzed. Multiply (5) with $\sin\theta_1$, multiply (6) with $\cos\theta_1$, then subtract them.

$$ x\sin\theta_1 - y\cos\theta_1 = 0 \quad (8) $$

$$ \tan\theta_1 = \frac{\sin\theta_1}{\cos\theta_1} = \frac{y}{x} \quad (9) $$

Thus,

$$ \theta_1 = atan\left(\frac{y}{x}\right). \quad (10) $$

Multiply (5) with $\cos\theta_1$, multiply (6) with $\sin\theta_1$, and use the trigonometric relationship.

$$ \sin\theta_j^2 + \cos\theta_j^2 = 1 \quad (11) $$

Hence

$$ \cos(\theta_2+\theta_3) = . \frac{x\cos\theta_1 + y\sin\theta_1 - a_2\cos\theta_2 - a_1}{a_3} \quad (12) $$

From (7),

$$ \sin(\theta_2+\theta_3) = \frac{z - a_2\sin\theta_2}{a_3}. \quad (13) $$

Substitute $\cos(\theta_2+\theta_3)$ and $\sin(\theta_2+\theta_3)$ from (12) and (13) into (11).

$$ A.\sin\theta_2 + B.\cos\theta_2 = D. \quad (14) $$

Where

$$ A = -z. \quad (15) $$

$$ B = a_1 - (x\cos\theta_1 + y\sin\theta_1). \quad (16) $$

$$ D = \frac{2a_1(x\cos\theta_1 + y\sin\theta_1) + a_3^2 - a_2^{2\,2}}{2a_2} + . \frac{-a_1^2 - z^2 - (x\cos\theta_1 + y\sin\theta_1)^2}{2a_2} \quad (17) $$

From (14),

$$ A = r\cos\phi. \quad (18) $$

$$ B = r\sin\phi. \quad (19) $$

Then

$$ \emptyset = atan\left(\frac{B}{A}\right). \quad (20) $$

$$ r = \pm\sqrt{A^2 + B^2}. \quad (21) $$

Equation (14) can be written as

$$ \cos\phi\sin\theta_2 + \sin\phi\cos\theta_2 = \frac{D}{r}. \quad (22) $$

$$ sin(\phi + \theta_2) = \frac{D}{r}. \quad (23) $$

From (11),

$$\cos(\phi+\theta_2) = \pm\sqrt{1-\sin^2(\phi+\theta_2)}$$
$$= \frac{\pm\sqrt{r^2-D^2}}{r}. \quad (24)$$

Thus

$$\tan(\phi+\theta_2) = \frac{D}{\pm\sqrt{r^2-D^2}}. \quad (25)$$

$$\theta_2 = -\emptyset + atan\left(\frac{D}{\pm\sqrt{r^2-D^2}}\right). \quad (26)$$

Substitute the value of ϕ and r in (20) and (21),

$$\theta_2 = -atan\left(\frac{B}{A}\right) + atan\left(\frac{D}{\pm\sqrt{r^2-D^2}}\right). \quad (27)$$

There are two answers of the solution depending on the mechanical constrains.

From (12) and (13), θ_3 can be determined.

$$\theta_3 = atan\left(\frac{z-a_2\sin\theta_2}{x\cos\theta_1+y\sin\theta_1-a_2\cos\theta_2-a_1)-\theta_2}\right). \quad (28)$$

The joint angles $\theta_1, \theta_2,$ and θ_3 are derived from the known foot position $x, y,$ and z .

$$\theta_1 = atan\left(\frac{y}{x}\right). \quad (29)$$

$$\theta_2 = -atan\left(\frac{B}{A}\right) + atan\left(\frac{D}{\pm\sqrt{r^2-D^2}}\right). \quad (30)$$

$$\theta_3 = atan\left(\frac{z-a_2\sin\theta_2}{x\cos\theta_1+y\sin\theta_1-a_2\cos\theta_2-a_1)-\theta_2}\right). \quad (31)$$

III. HARDWARE DESIGN OF THE QUADRUPED ROBOT

The quadruped robot, designed and developed at AIT, has 12 degrees of freedom and is actuated by 12 dc motors. Each leg contains 3 degrees of freedom. The hardware specification of the quadruped robot is provided in table2.

TABLE II. HARDWARE SPECIFICATION OF THE QUADRUPED ROBOT

Specification	value
Length	400mm
Width	281mm
Height	285mm
Weight	10,25kg
Battery	12Vx2
Degree of freedom	12DoF
DC motor power	18Wx12

The controller for the robot is divided into two levels: low level controller and the high level controller. The low level controller is used to control each joint in the legs while the high level controller is used to control the stability of the robot and to generate gait patterns.

(a)

(b)

Fig. 2. D-H parameters of a leg of AIT quadruped robot

All the controllers are implemented on Arduino controllers. The robot uses distributed control architecture for the low level controller. Six Arduino UNOs are used to control 12 DOF of the legs. The high level controller uses two Arduino MEGAs. One of the Arduino Mega is used as the gait generator, while the other is used for balancing control. The gait generator sends the gait commands to the joint controllers via UART, meanwhile the two Arduino MEGAs communicate each other using I2C. In balancing and attitude control, the robot uses a MEMS IMU consisting of 3-axis accelerometer and 3-axis gyroscope. The schematic diagram of the controller is shown in figure 3.

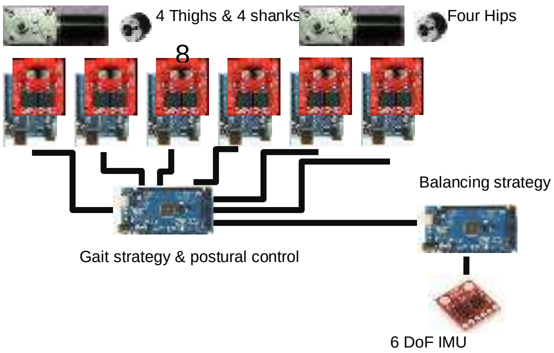

Fig. 3. Schematic diagram of the controller of the quadruped robot

Sinusoidal gait pattern is applied during the swing phase and linear gait pattern during the stance phase. Not every setting of the sinusoidal parameter provides good trotting performance for the quadruped robot. The important sinusoidal parameters are the amplitude (length of the step) and the frequency (speed of the step) of the gait pattern. These parameters affect the stability of the robot trotting. Higher frequency of trotting causes vibration in the robot. The length of the step relates the distance of the CoG shift. When the quadruped robot is trotting forward, its CoG is shifted forward. Six DoF IMU is used to measure the body attitude and fed to the controller for balancing control.

During trotting, stability of the robot is monitored from the trunk attitude. The pitch and roll angles of the trunk are measured, then CoG of the quadruped robot is shifted according to these angles. If the trunk pitch angle is positive, head up, then the CoG will be shifted forward along the X axis in positive direction. The CoG will be shifted backward if the trunk pitch angle is negative, tail up. Along with the Y axis as well, the CoG will be shifted to the right if the robot tilts to the left, and vice versa. The new CoG position is determined during trotting and updated according to the trunk attitude. The detail of the algorithm is shown in figure 4, while block diagram of the control system is shown in figure 5.

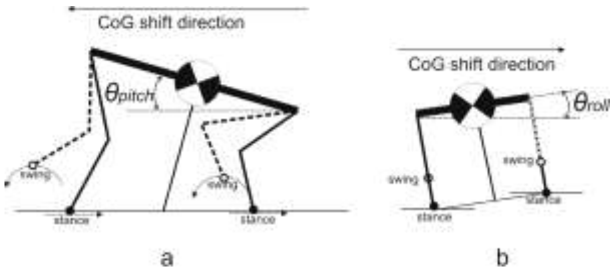

Fig. 4. Control algorithm for balancing during trotting: (a) Sagittal plane view, (b) Transverse plane view

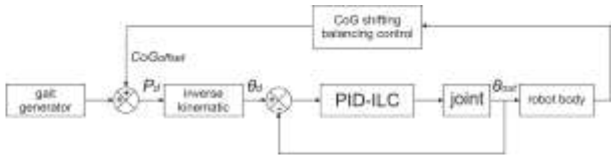

Fig. 5. Control block diagram of the quadruped robot

After linearization, the new CoG position is determined using

$x_{off} = x_{off} + k_x.\theta_{pitch}$

$y_{off} = y_{off} + k_y.\theta_{roll}$

where,

$xoff$: CoG offset in x direction

y_{off} : CoG offset in y direction

θ_{pitch} : pitch angle of the body (x direction)

θ_{roll} : roll angle of the body (y direction)

Gait pattern for forward trotting is shown in figure 6 whereas gait pattern for right turning is shown in figure 7.

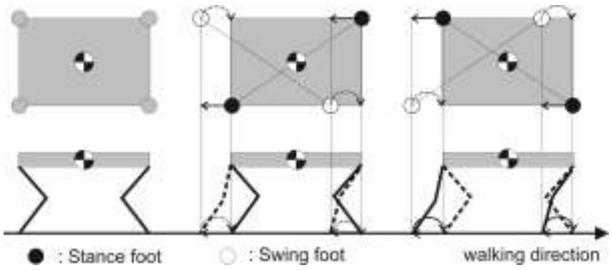

Fig. 6. Gait pattern for forward trotting

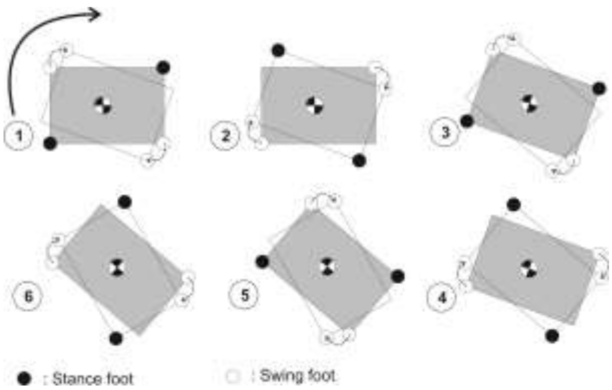

Fig. 7. Gait pattern for right turning

Leg joints are controlled using a hybrid PID-ILC. ILC is a relatively new control technique used to improve input signal of the system that executes the same trajectory repeatedly. This technique is capable to improve the transient response and the tracking performance [4]. Normally, PID gains should be set to low values. High PID gains may cause vibration in the system, especially if the natural frequency of the system was not investigated properly. ILC is applied to adjust the manipulated control signal until the desired trajectory is achieved. Control signal of ILC is determined from

$$u_j = u_{j-1} + k_d \dot{e}_{j-1}(t) + k_p e_{j-1}(t). \qquad (32)$$

This ILC control signal will be added to PID control signal. Thus, hybrid PID-ILC control signal is determined from:

$$u = k_p e_j(t) + k_d \dot{e}_j(t) + k_i \int e_j(t)dt + u_j. \qquad (33)$$

The block diagram of the system is depicted in figure 8.
where,

u_j : ILC control signal
k_p : proportional gain
k_d : derivative gain
k_i : integral gain
e_j : error between desired and actual outputs $(y_d - y_j)$
j : iteration number

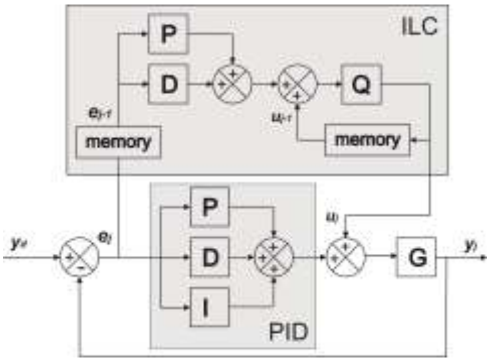

Fig. 8. Block diagram of hybrid PID-ILC [3]

IV. Experimental Results

Control performance of the leg joint controller is tested by sinusoidal gait pattern. Before applying ILC, the system has large steady-state error. However, the system is stable as shown in figure 9.

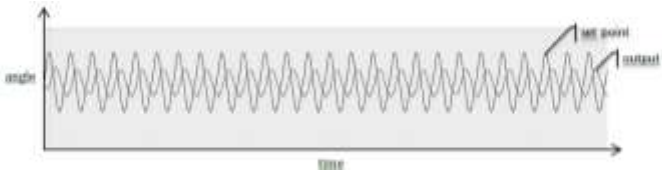

Fig. 9. Response from PID controller

After applying hybrid PID-ILC, the system is able to reach the trajectory set point after 10 iterations as shown in figure 10. The phase different is due to the filtering of the output. The result shows satisfactory output with low steady-state error.

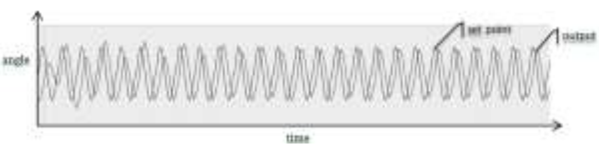

Fig. 10. Response from hybrid PID-ILC

At the beginning, big trajectory tracking error is observed. However after few numbers of iterations, the output of join angle can track the desired trajectory as shown in figure 11.

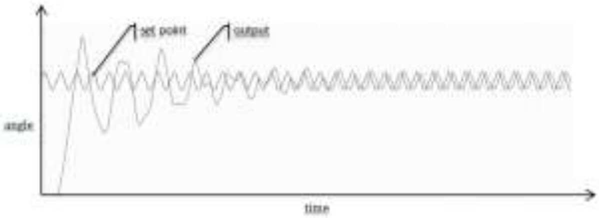

Fig. 11. Trajectory tracking performance of hybrid PID-ILC

By applying balancing control, the trunk attitude during trotting has less fluctuation. Figure 12 shows the trunk attitude without balancing control during trotting. Figure 13 shows the trunk attitude with balancing control.

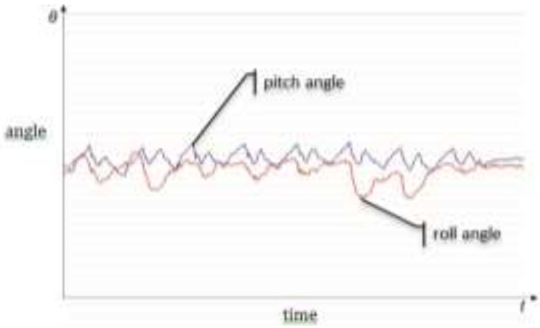

Fig. 12. Trunk attitude without balancing control, angle fluctuation ±11.4 deg

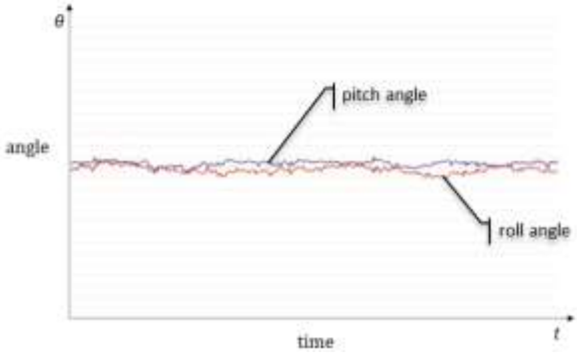

Fig. 13. Trunk attitude with balancing control, angle fluctuation: ±3.7 deg

V. Conclusion and Further Work

A quadruped robot has been developed at AIT. Dynamic walking was implemented via trotting gait pattern. The quadruped robot could successfully move forward, walk in place, and rotate to the right and to the left during trotting. The foot material was selected for proper damping. The damping softened landing impact. The CoG analysis and the gait pattern design were applied to stabilize the trunk attitude. The CoG shifting method improved the trunk attitude. Without balancing control, the pitch and roll angles are fluctuated about ±11.4 degree. However after applying the stability control, the angles were improved to only about ± 3.7 degree.

In the further work, a push recovery control algorithm for the quadruped robot will be designed. This algorithm is used to prevent the robot from tip over when the external force (disturbance) is applied to the robot.

References

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