

10th ICSE 2019

ABSTRACT

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No	Code	Title	Page
1	EDU-1	Role of Teaching English in Engineering Education: The Case Study in YTU Context	1
2	EDU-2	Potential Benefits of Transition into Independent Research-based Work in Postgraduate Programmes in Engineering Education Institutions	2
3	EDU-3	Developing and Implementing a Continuous Improvement Process in the Department of Metallurgical Engineering and Materials Science at Yangon Technological University	3
4	EE-1	Foot Trajectory Generation for Climbing Upstairs of a Biped Robot	4
5	EE-2	Epitaxial Tin Oxide Films on Sapphire Substrate Grown by Mist Chemical Vapor Deposition	5
6	EE-3	Image Details Preservation using Two-step Mixed Noise Removal Method with Interpolation	6
7	EE-4	Numerical Investigation of Carrier Mobility and Electrical Characteristics on Gallium Arsenide-Based MOSFET Design	7
8	EE-5	Speech and Non-Speech Identification and Classification Using KNN Algorithm	8
9	EE-6	Design and Implementation of Bandpass Filter for Heart Disease Classification from ECG Signal	9
10	EE-7	P-N Junction Formation and Metallization Process with Phosphorus Dopant on P Type Silicon Wafer Substrate	10
11	EE-8	Evaluation of Normal Load Parameters under Steady State for a Synchronous Generator Using Finite Element Method Magnetics	11
12	EE-9	Design and Performance Analysis of Three-phase Induction Motor by Finite Element Method	12
13	EE-10	Investigation of Optical Properties in GaN/InGaN/GaN Quantum Well Light Emitting Diodes Based on Numerical Analysis	13
14	EE-11	Performance Analysis of Power Flow Control by Using UPFC and DPFC	14
15	EE-12	Analysis of Quantum Mechanical Spatial Field Based on Metal-Semiconductor Stripe Structure for High Performance Devices by FDTD Techniques	15
16	EE-13	FPGA Based Different Frequency PWM Technique for Voltage Mode Control of Double Boost DC-DC Converter	16
17	EE-14	Improvement of System Performance Based on Isolated Interlink Converter in Microgrid System	17
18	EE-15	R-R Intervals Estimation with Doppler Sensor Using Viterbi Algorithm	18
19	EE-16	Simulation Of a Micro-Hydro Power Plant In Off-Grid Region	19
20	EE-17	Design and Analysis of Linearly Square Microstrip Patch Antenna for GPS Application	20

ICSE2019-EE-1

Foot Trajectory Generation for Climbing Upstairs of a Biped Robot

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Abstract - For a biped robot to be able to climb up and down stairs, the robot must be capable of various type of foot motion and high path curvature of trajectory planning will be needed. Basic requirement for the trajectory planning is to achieve smooth walking pattern for the biped robot. This paper presents the foot trajectory for climbing up stairs of the biped robot. In order to meet the requirement of smooth trajectory planning, the trajectory is generated by cubic spline interpolation method. The smooth trajectory of the present algorithm is verified with Matlab figures. The present algorithm is also applicable for climbing down stairs of the biped robot.

Keywords - Biped Robot, climbing upstairs, cubic spline interpolation, foot trajectory, smooth

10th ICSE 2019

PROCEEDINGS

Volume 1

- * **ENGINEERING EDUCATION**
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**THE TENTH INTERNATIONAL CONFERENCE ON
SCIENCE AND ENGINEERING, 2019 (10th ICSE 2019)**

Scope

The Tenth International Conference on Science and Engineering, 2019 (10th ICSE 2019) has been organized by Yangon Technological University (YTU), Myanmar. The conference will be held in Yangon Technological University (YTU), Yangon, Myanmar from 7th to 8th December, 2019. The Tenth International Conference on Science and Engineering, 2019 (10th ICSE 2019) aims to bring together scientists, leading engineers, industry researchers, and candidates from postgraduate courses to share and exchange their knowledge, experiences, information, and research on science and technology.

The 10th ICSE 2019 will be held in accordance with the following objectives;

- ❖ To create opportunity for young generation scientists, engineers, technologists and technicians to gain international experience
- ❖ To get chance for gaining technical knowledge from the international experts who conduct seminars and workshops on science and technology
- ❖ To increase knowledge on science and technology by exchanging research information with international universities and research organizations
- ❖ To enhance research knowledge and experience contributing to the advancement of research capabilities in the country
- ❖ To gain experience in carrying out research activities in collaboration with international universities

A wide range of important themes in various fields of Science and Engineering will be addressed at the conference and those who are interested in science and technology are warmly welcome to participate in the 10th ICSE 2019. Participants are requested to submit a proposal of academic or research paper for a 15-minute presentation and 5-minute Q&A.

This international conference would encourage researchers and engineers to present and discuss recent advances in science and engineering. ICSE features paper presentation of the following science and engineering fields:

- **Electrical and Electronics**
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- **ICT**
(*CEIT, EC, Mechatronics*)
- **Manufacturing and Automation**
(*Mechanical, Mechatronics, Chemical, Textile, Aero, Metallurgy*)
- **Energy, Environment and Natural Sciences**
(*Civil, Biotechnology, Mining, Petroleum, Metallurgy, EP, EC, Nuclear Engineering, Geology, Mechanical, Textile, Chemical, Remote Sensing, Physics, Chemistry, Mathematics, Nuclear Engineering*)
- **Natural Disaster Prevention**
(*Civil, Architecture, EP, EC, CEIT, Mechatronics*)
- **Infrastructure**
(*Civil, Architecture, EP, EC, CEIT, Mechanical, Remote Sensing*)

➤ **Engineering Education**

(Civil, Biotechnology, Mining, Petroleum, Metallurgy, CEIT, EP, EC, Nuclear Engineering, Geology, Mechanical, Mechatronics, Textile, Chemical, Remote Sensing, Physics, Chemistry, Mathematics, English)

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Invited Speakers

Measurement of prefrontal cortex activity to attention conflicts in working memory by NIRS

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Department of Informatics, Faculty of Information Science and Electrical Engineering
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Post-Mining a holistic approach

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Water Cleaning System Using Polysaccharides Fibers**Prof. Hiroshi Tamura**

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Deposition of permanent magnet powders applied to miniaturized motors**Prof. Masaki Nakano**

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A Proposal of Element/Code Fixing Problem in Java Programming Learning Assistant System**Prof. Nobuo Funabiki**

Department of Electrical and Communication Engineering Okayama University, Okayama, Japan

Volume 1

No	Code	Title	Page
1	EDU-1	Role of Teaching English in Engineering Education: The Case Study in YTU Context	1
2	EDU-2	Potential Benefits of Transition into Independent Research-based Work in Postgraduate Programmes in Engineering Education Institutions	6
3	EDU-3	Developing and Implementing a Continuous Improvement Process in the Department of Metallurgical Engineering and Materials Science at Yangon Technological University	11
4	EE-1	Foot Trajectory Generation for Climbing Upstairs of a Biped Robot	15
5	EE-2	Epitaxial Tin Oxide Films on Sapphire Substrate Grown by Mist Chemical Vapor Deposition	19
6	EE-3	Image Details Preservation using Two-step Mixed Noise Removal Method with Interpolation	22
7	EE-4	Numerical Investigation of Carrier Mobility and Electrical Characteristics on Gallium Arsenide-Based MOSFET Design	27
8	EE-5	Speech and Non-Speech Identification and Classification Using KNN Algorithm	30
9	EE-6	Design and Implementation of Bandpass Filter for Heart Disease Classification from ECG Signal	35
10	EE-7	P-N Junction Formation and Metallization Process with Phosphorus Dopant on P Type Silicon Wafer Substrate	40
11	EE-8	Evaluation of Normal Load Parameters under Steady State for a Synchronous Generator Using Finite Element Method Magnetics	44
12	EE-9	Design and Performance Analysis of Three-phase Induction Motor by Finite Element Method	49
13	EE-10	Investigation of Optical Properties in GaN/InGaN/GaN Quantum Well Light Emitting Diodes Based on Numerical Analysis	54
14	EE-11	Performance Analysis of Power Flow Control by Using UPFC and DPFC	57
15	EE-12	Analysis of Quantum Mechanical Spatial Field Based on Metal-Semiconductor Stripe Structure for High Performance Devices by FDTD Techniques	62
16	EE-13	FPGA Based Different Frequency PWM Technique for Voltage Mode Control of Double Boost DC-DC Converter	66
17	EE-14	Improvement of System Performance Based on Isolated Interlink Converter in Microgrid System	71
18	EE-15	R-R Intervals Estimation with Doppler Sensor Using Viterbi Algorithm	76
19	EE-16	Simulation Of a Micro-Hydro Power Plant In Off-Grid Region	81
20	EE-17	Design and Analysis of Linearly Square Microstrip Patch Antenna for GPS Application	86
21	EE-18	An Experimental Study of Indoor Access Point Placement with Load Balancing AP Association for IEEE 802.11n WLAN	91
22	EE-19	A Method for Removing Non-Text Objects in Document Images	96
23	EE-20	Implementation of Human Detection Based on Histogram Oriented Gradients	102
24	EE-21	Implementation of Noise-free Audio Amplifier Design for Conference Room	107
25	EE-22	Machine Learning for Human Activity Recognition using Smartphone	112
26	EE-23	Weather Radar Echo Simulator for Software Defined Weather Radar Development	115
27	EE-24	Design and Implementation of Charge Controller for E-bike Station based on Solar Energy	120
28	EE-25	Statistical Features Based Classification of Normal and Epileptic EEG Signals	125
29	EE-26	Recognition of Emotion Expression from EEG Signals by Using SVM Classifier	130
30	EE-27	Classification of Imagine Right and Left-Hand Movement EEG Signals for BCI Application by Using Test Statistic Z-Distribution	134
31	EE-28	Design of Wideband Rectangular Microstrip Patch Antenna for 5G Applications	139
32	EE-29	Vision Based Dynamic Hand Gesture Recognition Approach to Control Power Point Presentation Processes	144
33	EE-30	Modelling and Control of DC Motors for Drawing Machine	149
34	EE-31	Analysis of I-V Characteristics and Bandgap Design for Homo Junction JFET Using Zinc Oxide Material with Numerical Simulation	154

No	Code	Title	Page
35	EE-32	Implementation of Real Time Driver Drowsiness Detection System using OpenCV and Dlib	159
36	EE-33	Modeling of UPFC with New Control Strategy for Transmission Line Capacity Improvement	164
37	EE-34	Development of Mho Type Distance Relay Model for Protection of High Voltage Transmission Line Using Matlab/Simulink	169
38	EE-35	Modeling and Analysis for PnO Algorithm and ANN Technique Used MPPTs for Stand Alone PV System	174
39	EE-36	Determination of Power System Stabilizer Location for Multi-machine Power System Based on Generators Swing Conditions	179
40	EE-37	Modeling and Simulation of PV based Charging Strategy for Improving the Performances of Li-ion Battery	184
41	EE-38	Direct Torque Control of Induction Motor using Space Vector Pulse Width Modulation	189
42	EE-39	Performance Analysis of D-STATCOM for Voltage Sag Mitigation	194
43	EE-40	Simulation and Implementation of PV-Based Controller for Battery Charging	199
44	EE-41	Performance Analysis of Reactive Power Compensation by Using Static Var Compensator (SVC)	204
45	ICT-1	Efficient Virtual Machine Allocation Model for Cloud Data Center	209
46	ICT-2	Sentiment Analysis for Travel and Tourism Domain Using Hybrid Approach	213
47	ICT-3	OCR Post-Processing Error Correction Based on Features-based Words Classification	218
48	ICT-4	An Overview of Named Data Networking and its Challenging Security Issues	223
49	ICT-5	Reducing Traffic between Controller and Switch in SDN Networks	226
50	ICT-6	Impact of Dependent and Independent Variables based on Ordinary Least Squares Method Using Test-Driven Development Approach	231
51	ICT-7	Effective Acoustic Feature Parameters for Emotion Estimation of Infant Crying Sound and Detection of Abnormal Lung Sound	236
52	ICT-8	DDoS Attack Detection Using XGBoost Classifier in Software Defined Network	241
53	ICT-9	Syllable Segmentation for Mon Language	246
54	ICT-10	Real Time Security System using Human Motion Detection	250
55	ICT-11	Sentiment Analysis of Myanmar News using Multi-layer Perceptron (MLP)	255
56	ICT-12	Detection of DDoS Attacks in IOT Sensor Data Using Machine Learning Techniques	260
57	ICT-13	Concise and Coherent Text Summary from Single Document Using Statistical Features	265
58	ICT-14	Face Sketch Construction System Using Graphics Pipeline Algorithm	270
59	ICT-15	Comparison of GRE, IPsec and GRE over IPsec for VPN	275
60	ICT-16	A Simple Compression Scheme for Unicode Myanmar Documents	280
61	ICT-17	Syllable based Myanmar Text to Speech System	284
62	ICT-18	Object Detection from CCTV Video by using FCNN Deep Learning Technique	289
63	ICT-19	Printed Document Authentication Technique Using Pixel Modification Based Watermarking	294
64	ICT-21	Statistics Measurement of Network Traffic in Software Defined Networking	299
65	ICT-22	Rating Prediction Using Reviews for Recommendation	304
66	ICT-23	Rule-based Myanmar Language Chatbot for Travel and Tourism Domain	307
67	MA-1	Kinematic Analysis for Automatic Egg Lifter in a Hatchery Farm	312
68	MA-2	Case Study of Manufacturing Processes in National Wood Industry for the Purpose of Modelling of Just-in-Time Inventory	316
69	MA-3	An Investigation on the Forecasting Methods for Predicting the Amount of Raw Materials for a Cement Factory in Myanmar	321
70	MA-4	Determination of Homogeneous Particle Distribution in Pneumatic Conveyance by Electrical Capacitance Tomography	326
71	MA-5	Isolation of Cuminaldehyde from Cuminum Cyminum Linn. (Zeyar) Seeds and Semisynthesis of Cyclamenaldehyde	329

No	Code	Title	Page
72	MA-6	Analysis of Root Stress for External Spur Gear for Various Contact Ratios	333
73	MA-7	Analysis of Stress-Strain Distribution in Deep Drawing Process by Using Finite Element Method	340
74	MA-8	Visco-Plastic FEM Analysis on the Ball Grid Array Solder Joints	345
75	MA-9	Quantized State Feedback Control System Using Dynamic Quantization and Model Predictive Control	350
76	MA-10	Stress Analysis of Ball Screw Drive System for a Small-Scale CNC Milling Machine	354
77	MA-11	Comparative Analysis of a Compressed Natural Gas Fuelled Single Cylinder SI Engine Performance	361
78	MA-12	Study on Wave-Breaking Phenomena of Full Hull Forms with and without Protruded Bows	366

Foot Trajectory Generation for Climbing Upstairs of a Biped Robot

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Keywords - Biped Robot, climbing upstairs, cubic spline interpolation, foot trajectory, smooth

I. Introduction

Biped robot is two legged robot and is expected to eventually evolve into one with human-like body. The biped robot has higher mobility than conventional wheeled robots especially when moving on rough terrain, steep stairs and in environments with obstacles [1]. Climbing up and down stairs is the typical common action of biped robot.

Since the biped robot tends to tip over easily, it is necessary to take stability. Stable walking can be achieved by centre of gravity (CG) control and Zero Moment Point (ZMP) control. The CG trajectory control can guarantee the stability of static walking while the ZMP trajectory control can realize stable dynamic walking. The ZMP is the point on the ground which the sum of all the moments of the active forces equals zero. In order to achieve stable dynamic walking, the ZMP must be kept the inside the support region [9].

The walk of the biped robot can be determined by controlling the hip and foot trajectories. In the single support phase, cubic polynomial is used to generate the hip and swing foot trajectories which satisfy the ZMP criterion [1]. The swing foot should follow the desired trajectory to avoid obstacles and to satisfy the landing constraints. In some research, cubic spline interpolation method is better than cubic polynomial for trajectory planning of biped robot [6].

Some other international and domestic academics have also relevant studies about the biped robot actions of climbing up and down stairs or slopes [2]. Based on the analysis of the actions of biped robots, in this paper we present the foot trajectory for climbing up stairs of biped robot. This paper organized as follows. Mathematical background of applied method is introduced in section II. In section III, the algorithm for foot trajectory are proposed and generated. Resulting trajectories are demonstrated with Matlab in Section IV. And finally, a conclusion is given in section V.

II. MATHEMATICAL BACKGROUND

The mathematical interpolation is one of the simplest methods utilized for obtaining the suitable curves with respect to the given break points that the robot must undergo. When there are various constraints such as ground conditions and various foot motions, the order of polynomial is too high, its computation is difficult and the trajectory may oscillate. To avoid this problem, cubic spline interpolating polynomial is used to generate the swing foot trajectory [6].

1. Cubic Spline Interpolation

In this section, theoretical concept of cubic spline interpolation is discussed. The cubic spline interpolation will be applied to find the trajectory planning of biped walking.

The fitting of polynomial curve to set data points has applications in trajectory planning of the biped walking. To be able to draw a smooth curve through data points that are not subject to error, mathematically, it is possible to construct cubic functions on sub interval. The resulting piecewise curve and its first and second derivatives are all continuous in the larger interval. The continuity of first derivative means that the graph will not have sharp corners. The continuity of second derivative means that the radius of curvature is defined at each point [4].

2. Piecewise Cubic Splines

Suppose that $\{(t_j, f_j)\}_{j=1}^n$ are n points, where $t_1 < t_2 < \dots < t_n$. The function $S(t)$ is called cubic spline if there exist $n-1$ cubic polynomials $S_j(t)$ with coefficients $a_{j,0}, a_{j,1}, a_{j,2}$ and $a_{j,3}$ that satisfies the following properties:

$$I. S(t) = S_j(t) = a_{j,0}(t - t_j)^3 + a_{j,1}(t - t_j)^2 + a_{j,2}(t - t_j) + a_{j,3}$$

$$\text{for } t \in [t_j, t_{j+1}] \text{ and } j = 1, 2, \dots, n-1$$

$$II. S(t_j) = f_j \text{ for } j = 1, 2, \dots, n.$$

$$III. S_j(t_{j+1}) = S_{j+1}(t_{j+1}) \text{ for } j = 1, 2, \dots, n-2.$$

$$IV. S'_j(t_{j+1}) = S'_{j+1}(t_{j+1}) \text{ for } j = 1, 2, \dots, n-2.$$

$$V. S''_j(t_{j+1}) = S''_{j+1}(t_{j+1}) \text{ for } j = 1, 2, \dots, n-2.$$

Property I states that $S(t)$ consists of piecewise cubics. Property II states that piecewise cubics interpolate the given sets of data points. Property III and IV require that the piecewise cubic represents a smooth continuous function. Property IV states that the second derivatives of the resulting function are also continuous.

A piecewise function is constructed as follows [4].

$$S(t) = \begin{cases} S_1(t) & \text{if } t_1 \leq t \leq t_2 \\ S_2(t) & \text{if } t_2 \leq t \leq t_3 \\ \vdots & \\ S_{n-1}(t) & \text{if } t_{n-1} \leq t \leq t_n \end{cases}$$

where $S_j(t)$ is a cubic polynomial defined by

$$S_j(t) = a_{j,0}(t - t_j)^3 + a_{j,1}(t - t_j)^2 + a_{j,2}(t - t_j) + a_{j,3}, j = 1, 2, \dots, n - 1.$$

By using the properties, I, II, III and IV, we can get the coefficients of cubic spline interpolation as follow:

$$a_{j,0} = \frac{m_{j+1} - m_j}{6h_j},$$

$$a_{j,1} = \frac{m_j}{2},$$

$$a_{j,2} = a_{j,3} - \frac{h_j(2m_j + m_{j+1})}{6},$$

$$a_{j,3} = f_j$$

where $m_j = S_j''(t_j)$ and $h_j = t_{j+1} - t_j$.

Construction of natural spline interpolation

There exists a unique cubic spline with the free boundary conditions $m_1 = m_n = 0$ [3]. The linear system equations for finding m_2, m_3, \dots, m_{n-1} connected with natural spline condition are

$$2(h_1 + h_2)m_2 + h_2m_3 = u_2$$

$$h_{j-1}m_{j-1} + 2(h_{j-1} + h_j)m_j + h_jm_{j+1} = u_j \text{ for } j = 3, 4, \dots, N - 2$$

$$h_{n-2}m_{n-2} + 2(h_{n-2} + h_{n-1})m_{n-1} = u_{n-1}$$

where $u_j = 6(d_j - d_{j-1}), j = 2, 3, \dots, n - 1$ and

$$d_j = \frac{f_{j+1} - f_j}{h_j}.$$

3. *Function imitation:* Cubic splines are not necessary to be simple to determine a well-behaved function to fit any data set. This is, however, usually not the case. Thus, the cubic spline technique is used to generate a function to fit the data. Moreover, it can be shown that the data generated by a particular function is interpolated by a spline which more or less like the original function. This is testimony to the consistency of spline [4].

III. FOOT TRAJECTORY FOR WALKING UPSTAIRS OF A BIPED ROBOT

An anthropomorphic biped robot is considered as a reference model where each leg consists of a thigh, a shank and a foot. The under study model has six degree of freedom in sagittal plane including three degree of freedom (DOF) in the hip joint, one in each knee joint, and two in each ankle joint. If both foot trajectories and hip trajectory are known, all joint trajectories of the biped robot will be determined by kinematic constraints. The climbing up stairs pattern can therefore be denoted by uniquely by both foot trajectories and hip trajectory. In this paper, we only discuss the swing foot trajectory in the sagittal (XZ) plane.

For a sagittal plane, each foot trajectory can be denoted by a vector

$X_a = [x_a(t), z_a(t), \theta_a(t)]^T$ where $(x_a(t), z_a(t))$ is the coordinate of the ankle position, and $\theta_a(t)$ denotes the angle of the foot [1].

If the biped robot climbs up stairs, the foot trajectories can be obtained by varying the values of start and end positions [2]. For example, $x_{fe} = x_{fs} + 2L_s$, $z_{fe} = z_{fs} + 2S_h$ where (x_{fs}, x_{fe}) and (z_{fs}, z_{fe}) are initial and final position of one climbing cycle, L_s is stair length and S_h is stair height shown in Fig 2.

The Proposed Trajectory Planning Algorithm

1. The time interval for the breakpoints of one climbing step is previously specified.
2. The position constraints for the breakpoints of one climbing step is formulated.
3. The whole trajectory between the breakpoints of one climbing step is derived by applying cubic spline interpolation.

Algorithm step 1: Time interval for One Climbing step

Assuming that the entire sole surface of the right foot is in contact with the stairs at $t = 0$ and $t = T_c + T_d$. T_c , T_d and T_m are the interval of single support phase, the double support phase and the foot swing over the middle stairs. The time interval for one climbing step as shown in Fig 1 is specified as follows:

1. Place (entire sole contact) ($t = 0$)
2. Deploy (heel off) ($t = T_d$)
3. Swing (lift on the air) ($t = T_m$)
4. Deploy (heel contact) ($t = T_c$)
5. Place (entire sole contact) ($t = T_c + T_d$)

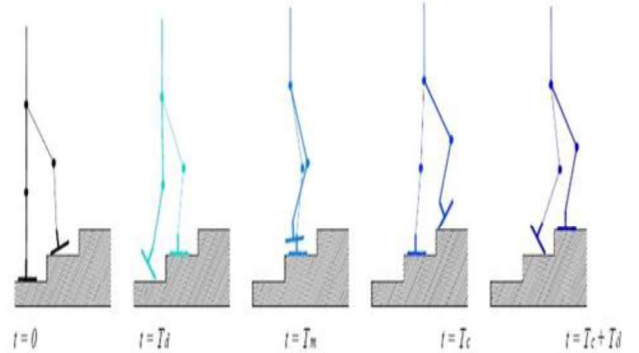


Fig. 1 Time interval for one climbing step

Algorithm step 2: Position constraints for the breakpoints of one climbing step

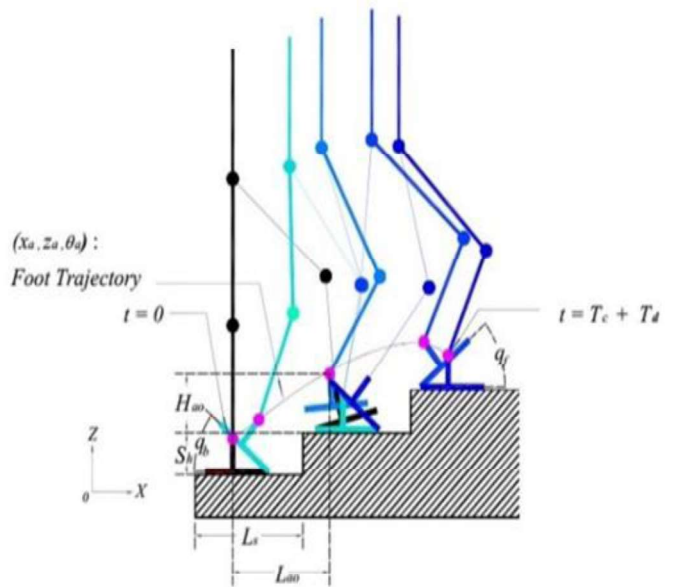


Fig. 2 One climbing stairs cycle of the biped robot

Letting l_{an} be the height of the foot, l_{af} is the length of the ankle joint to the toe and l_{ah} is the length of the ankle joint to the heel. Letting q_b and q_f be the designated angles of the swing foot as it leaves and lands on the stairs.

The position constraints for breakpoints of one climbing cycle are described by following [7]:

$$x_a(t) = \begin{cases} 0, & t = 0 \\ l_{an}\sin q_b + l_{af}(1 - \cos q_b), & t = T_d \\ l_{ao}, & t = T_m \\ 2L_s - l_{an}\sin q_b - l_{ab}(1 - \cos q_f), & t = T_c \\ 2L_s, & t = T_c + T_d \end{cases}$$

$$z_a(t) = \begin{cases} l_{an}, & t = 0 \\ l_{af}\sin q_b + l_{an}\cos q_b, & t = T_d \\ H_{ao} + S_h, & t = T_m \\ 2S_h + l_{ab}\sin q_f + l_{an}\cos q_f, & t = T_c \\ 2S_h + l_{an}, & t = T_c + T_d \end{cases}$$

$$\theta_a(t) = \begin{cases} 0, & t = 0 \\ q_b, & t = T_d \\ q_f, & t = T_c \\ 0, & t = T_c + T_d \end{cases}$$

Algorithm step 3: The whole trajectory between the break points of one climbing cycle

The cubic spline interpolation method is applied to find the trajectory planning of biped robot. Firstly, the values of parameters for one climbing step are proposed in Table 1.

TABLE 1
PARAMETERS OF ONE CLIMBING CYCLE

parameter	value
T_d	0.18 s
T_m	0.4 s
T_c	0.9 s
l_{an}	10 cm
l_{ab}	10 cm
l_{af}	13 cm
D_s	50 cm
l_{ao}	40 cm
H_{ao}	15 cm
L_s	39 cm
S_h	13 cm
q_b	0.7 rad
q_f	0.7 rad

By applying the cubic spline interpolation in section II, finally we get the complete one climbing step foot trajectory is obtained as follows:

$$x_a(t) = \begin{cases} 512.16t^3 + 36.18t, & t \in (0,0.18) \\ -638.29(t-0.18)^3 + 276.57(t-0.18)^2 + 85.96(t-0.18) + 9.50, & t \in (0.18,0.4) \\ 103.17(t-0.4)^3 - 144.70(t-0.4)^2 + 114.97(t-0.4) + 35, & t \in (0.4,0.9) \\ -18.63(t-0.9)^3 + 10.06(t-0.9)^2 + 47.65(t-0.9) + 69.21, & t \in (0.9,1.08) \end{cases}$$

$$z_a(t) = \begin{cases} 169.67t^3 + 27.97t + 10, & t \in (0,0.18) \\ -210.22(t-0.18)^3 + 91.62(t-0.18)^2 + 44.46(t-0.18) + 16.02, & t \in (0.18,0.4) \\ -26.01(t-0.4)^3 - 47.12(t-0.4)^2 + 54.25(t-0.4) + 28, & t \in (0.4,0.9) \\ 159.53(t-0.9)^3 - 86.15(t-0.9)^2 - 12.39(t-0.9) + 40.09, & t \in (0.9,1.08) \end{cases}$$

For the pre-swing phase and post-swing phase,

$$\theta_a(t) = \begin{cases} -8.57t^3 + 4.17t & t \in (0,0.18) \\ 8.57(t-0.9)^3 - 4.63(t-0.9)^2 - 3.33(t-0.9) + 0.7 & t \in (0.9,1.08) \end{cases}$$

IV. SWING FOOT HIP TRAJECTORY BY MATLAB PROGRAM

In this section the numerical result of swing foot trajectories that have been derived in section III are checked by drawing graphs with Matlab figures. So that all the results we obtained are correct can be checked to see whether they are correct or not.

In Fig.3, the resulting trajectory of X-axis is demonstrated. It can be clearly seen that the demonstrated trajectory is smooth and continuous.

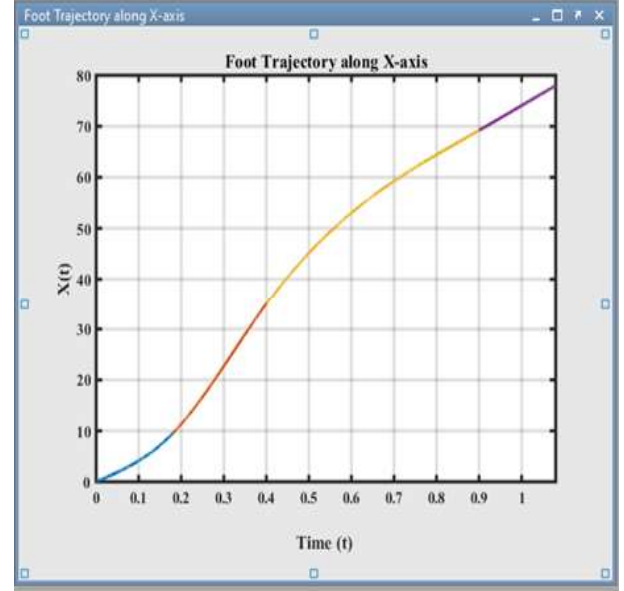


Fig. 3 Swing foot trajectory along X-axis

In Fig.4, the resulting trajectory of Z-axis is demonstrated. The demonstrated trajectory is a smooth curve through data points that are not subject to error as in Fig.3.

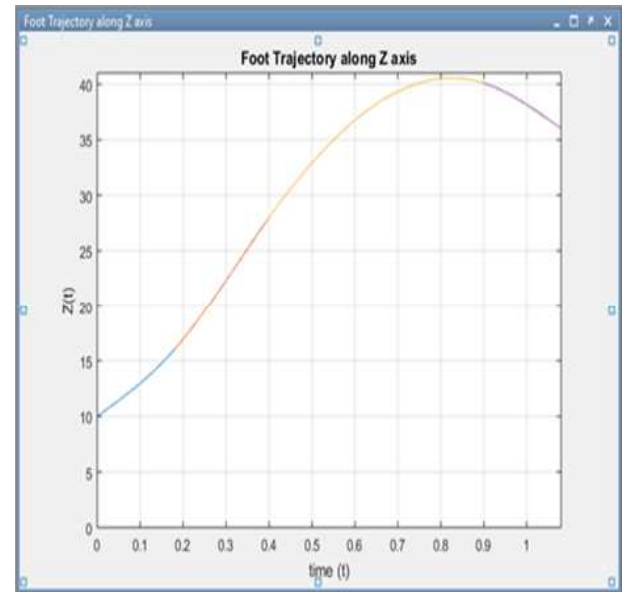


Fig. 4 Swing foot trajectory along Z-axis

In Fig.5, the resulting trajectory of along angle for pre-swing foot and post-swing foot is demonstrated. This trajectory is a smooth curve as in Fig.3 and 4.

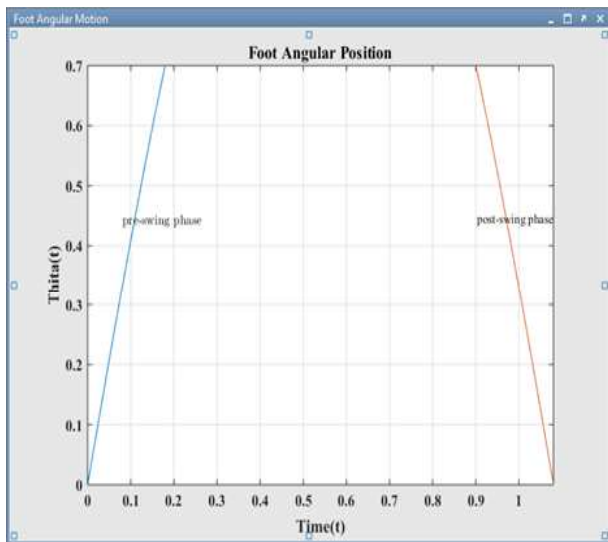


Fig. 5 Foot angular motion

It is clearly seen that the resulting trajectories are smooth and continuous due to the properties of cubic spline interpolation.

V. CONCLUSIONS

In this paper, foot trajectory for climbing upstairs of a biped robot has been generated. As mathematical background of this paper, cubic spline interpolation has been described. And then, theoretical background of climbing up stairs trajectory has been discussed. Finally, the goal of this research, the climbing upstairs trajectory generated by cubic spline interpolation, has been approached and derived. The resulting trajectories for applying this interpolation method are smooth and continuous. Future study will focus on stable hip trajectory for climbing upstairs of the biped robot from the mathematical point of view.

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