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Novel Gait for an Anthropoid and Its Joint Demeanors while Stepping Up and Down Stairs

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Abstract A biped humanoid is considered as an open kinematic chain consisting of two sub chains as legs and torso which connected at a common point, the hip. When defining the gait for stepping stairs, there exist two main phases which are Single Support Phase (SSP) and Double Support Phase (DSP). The challenge is to make the anthropoid stable in its upright position without losing it while performing the two alternating phases, SSP and DSP. In this paper a novel gait for an anthropomorphic system to step up-down stairs is formulated and experimented using BIOLOID humanoid platform. The gait is merged with various poses which are excogitated through the Forward and Inverse Kinematics (FK and IK) analysis based on Denavit-Hartenberg (D-H) representation and Geometric-Trigonometric (G-T) formulation techniques. The main focus of this paper is to represent and analyze the diverse behaviour of the various joint actuators of the robot while performing the step up and down stairs.

Keywords Humanoid Robot, Stairs Climbing Gait, Step Up Down Stairs, Gait Analysis

1. Introduction

Gait for moving forward or backward or even turning is defined as the alternating phases of single and double support mode of an anthropomorphic robot. The DSP is the phase when both legs are in contact with the navigation surface. In SSP only a single leg is in contact with the ground which is called as the stance leg while the other one is called as the swing leg. The main requirement of the robot is to alternate the phases by maintaining the displacement of the horizontal components such as the Centre of Mass (CoM), with strictly monotonic fashion which means the CoM should be stable without rocking forward and backward. In order to understand the gait, it is necessary to visualize the human planes of sections. The Sagittal Plane divides the body into right and left sections. The Frontal or Coronal Plane separates the body into front and back portions. Finally the Transverse Plane is perpendicular to both the Sagittal and Frontal Planes and divides the body up and down portions at the hip position of the body [1,2]. These three different planes are represented in Figure 1.

Leonardo de Vinci is considered as the first man who has drawn a humanoid mechanism in 1495 [3,4]. Construction and development period of humanoid system commences in the 19th century when John Brainerd invented the Steam Man in 1865 [4,8]. At the beginning of 20th century an evolutionary number of humanoid systems appear such as ELEKTRO, BIPER, Tron-Xm, H6, Waseda Legged series, WABOT, WABIAN family, WAP series, SAIKO, E0 to E6, P1 to P3 and so on [4]. Jumping robot, Spring Turkey, Spring Flamingo, Uniroo, Biped Planar, and 3D Biped were the remarkable invention from MIT having noteworthy performance on walking and running movements with dynamic and stable gait. ASIMO the currently most advance humanoid system is demonstrated in the year 2000 [5,6,9]. BIP2000, AIBO, RABBIT, KHR, HUBO, HRP, HOAP, ROBIAN, NAO, iCub, CB2, MAHRU, REEM, QRIO are some of the greatest anthropoid platform came out during the last ten years [4-9].

A type of walking pattern and sensory feedback control strategy were proposed for an anthropomorphic robot stepping up stairs, in 2008 [10]. The parameter selection for the designed gait was excogitated based on the Constrained Nonlinear Optimization Problem (CNOP). Using the Reinforcement Learning (RL) method the control parameters for feedback were adjusted for stepping up the stairs. An algorithm was proposed by S. H. Kim and Y. Sankai to generate extended task for anthropoid to perform various movements including the ascending steps [11]. The third-order Bezier curve was adopted for this experiment where the desired trajectory was possible to accomplish by modifying the control parameters. Accelerometer and Force sensor based control mechanism for a humanoid system stepping up stairs was explicated by T. H. S. Li et al. [12] where an autonomous control strategy was proposed. Self balancing gait using Fuzzy Logic (FL) and Zero Moment Point (ZMP) were

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adopted for this experiment and ten step stairs climbing strategy was demonstrated with successful accomplishment. Robust model based real time 3D tracking strategy was demonstrated in 2007 where a programmable graphics hardware was used to operate the humanoid robot [13].

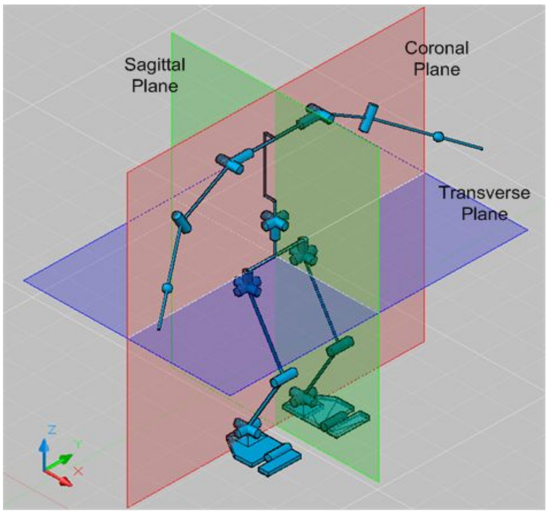


Figure 1. Three different Section Planes of an anthropomorphic system

All the methods, mentioned above, have demonstrated with the robustness of their individual gaits having the same type of foot placing strategy as, Flat-Lifting and Flat-Landing (FL-FL) footsteps. This technique is feasible for slow walking patterns. In this paper a novel gait is designed and demonstrated using the BIOLOID humanoid platform where human like walking is demonstrated and can be abridged as, Heel-Contact and Toe-Off (HC-TO) walking strategy. This particular method may provide the ability to the anthropomorphic system for faster walking and even for running. The paper also represents the CoP-CoM tracking strategy which is excogitated by following the ZMP technique and can be defined as, tracking the Centre of Pressure (CoP) movements by CoM of the system. The paper mainly focuses on the gait design strategy and various movement behaviors of the joint actuators in performing the gait for step up-down stairs.

Pre formulation of gait vector and designing the gaits for Ascending-Descending stairs are presented in Section 2. In Section 3, the various angular positions of the joint actuators are tabulated. The deportments of the joint actuators are also plotted and analyzed in the same section. Finally, Section 4 presents the abridgement of the paper.

2. Gait Analysis and Design

2.1. Analysis and Pre Formulation

Humanoid gaits are the combination of various postures and poses. Some series of poses can be accumulated together as a page and a group of pages are combined with an adjustable sequence to make the robot able to achieve the next stage of the performing gait. If the system begins to execute a particular action, the execution of a particular page should be completed before the start of the next action. A mathematical expression for the execution process can be defined with $\vec{P}$, which is considered as a vector and a function of the joint vector $\vec{Q}$. The $\vec{P}$ indicates the pose of the humanoid for a certain moment of time in a particular direction while executing a page. If the start and end poses of a single page is indicated as P_i and P_f, a general equation can be formulated as shown in Equation (1) and Equation (2) where $\vec{Q}_{(i)}$ is a set of the joint vectors of *'i'*th pose contingent on the *'n'* DoF of the system.

$$\vec{P} = \overrightarrow{P_i P_f} = \sum_i^f f(\vec{Q}_{(i)}) \quad (1)$$

$$\vec{Q}_{(i)} = \{\vec{Q}_{1(i)}, \vec{Q}_{2(i)}, \vec{Q}_{3(i)} \dots\dots\dots, \vec{Q}_{n(i)}\} \quad (2)$$

2.2. Defining the Stair Constraints

Moving up and down stairs are the complex task for a humanoid where more stable gaits are required. During the climbing stairs, the humanoid has to move its CoM position upwards to shift its torso on the next step which is more complex than moving the CoM while navigating on flat surface. Step down stairs is also the difficult and complex chore to remain stable while gravitational force attracts the CoM point. Figure 2 represents the designed stairs having two steps up and down. Height of the each step is about 3.1 cm which makes 6.2 cm height in total for the two steps. The stairs are especially designed for the humanoid with the necessary space to place its feet on the steps.

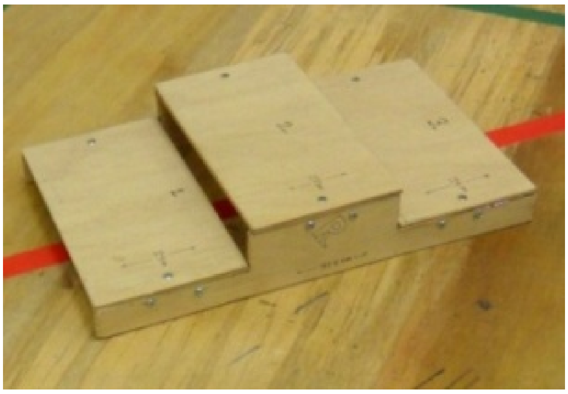


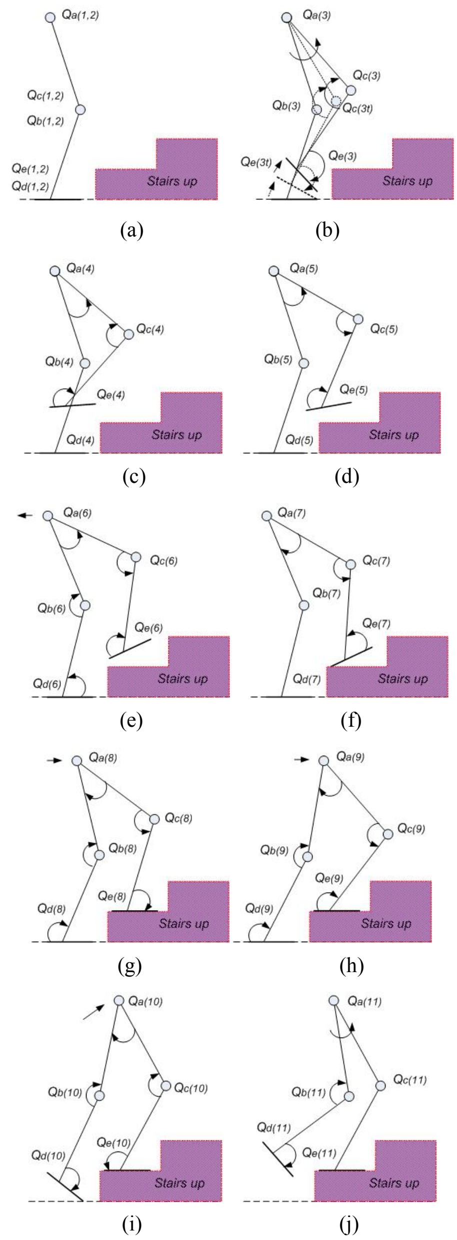
Figure 2. Two step stairs model

2.3. Gait for Ascending Stairs

As the two swing modes are involved to gait the humanoid for a single step up stairs, the designed gait is conceived with fifteen poses. The first three poses, shown in Figure 3(a) and (b) are considered as same as the walking or obstacle overcoming gait design. The first swing phase for the action leg has to execute five poses to settle the action foot on the step of the stairs as shown in Figure 3(b) to (f). During this action the CoM of the system is shifted backwards for a little distance to make the humanoid stable without falling down, Figure 3(e). With the proper placement of the front foot on the step, the humanoid moves its torso forward in two different poses, Figure 3(g) and (h). Before the beginning of the second swing phase with the rear foot, the anthropoid moves its CoM gradually upwards to fix its stability by front foot support, Figure 3 (i). The second swing phase continues with the next four poses as shown in Figure 3 (j) to (m) and finally the robot moves its torso upwards to come to the Action Pose again. The whole process can be performed in two ways depending on the action leg, right or left. As a result, the algorithm is designed with two functions, *StUP_Left( )* and *StUP_Right( )*. The mathematical description of the procedure can be presented as follows where $\vec{P}_{SU}$ stands for Step Up vector.

$$\vec{P}_{SU} = \overrightarrow{P_i P_f} = \sum_{i=1}^{f=15} f(\vec{Q}_{(i)}) = \sum_{i=1}^{f=15} f(\vec{Q}_{a(i)}, \vec{Q}_{b(i)}, \vec{Q}_{c(i)}, \vec{Q}_{d(i)}, \vec{Q}_{e(i)}) \quad (3)$$

Here $\vec{Q}_{(i)}$ stands for a set of the joint vectors in a certain pose of the system. Figure 3 presents the design of the fifteen poses to perform step up stairs.



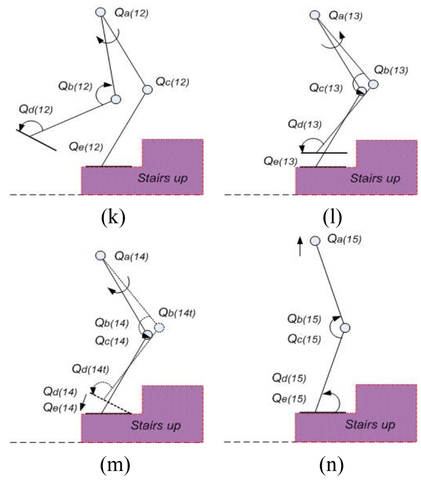
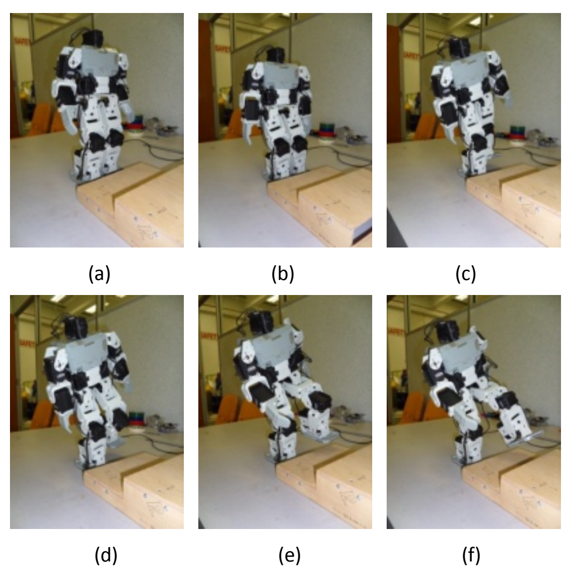


Figure 3. Fifteen different poses for a single step up of the stairs, (a) Action Pose and $Tilt_a$ Pose (two poses), (b) $DS\text{-}SS_a$ Pose, (c) $Foot_a$ Lifting Pose, (d) $Foot_a$ Forward Pose, (e) $Foot_a$ Adjust Pose, (f) $SS\text{-}DS_a$ Pose, (g) $SS\text{-}DS_a$ Complete Pose, (h) $Tilt_b$ Pose, (i) CoM Lifting Pose, (j) $DS\text{-}SS_b$ Pose, (k) $Foot_b$ Lifting Pose, (l) $Foot_b$ Forward Pose, (m) $SS\text{-}DS_b$ Pose and (n) Action Pose

The *StUP_Left ( )* and *StUP_Right ( )* functions are defined where the series of poses are executed sequentially. To define the main function for the Stair Up Step, *StUP ( )* is defined, Figure 4. The function takes a parameter value indicating the left or right leg in action to perform the task. The return value, 0, represents the system as in Action Pose and the completion of the operation successfully.

```
Declare StUP (parameter: integer i)
        If i is equal to 1
                Call StUP_Left ();
        End of if
        Elseif i is equal to 2
                Call StUP_Right ();
        End of elseif
        Return 0;
End of StUP
```

Figure 4. Defining the Step Up function as *StUP ( )* with a parameter value indicating the action leg



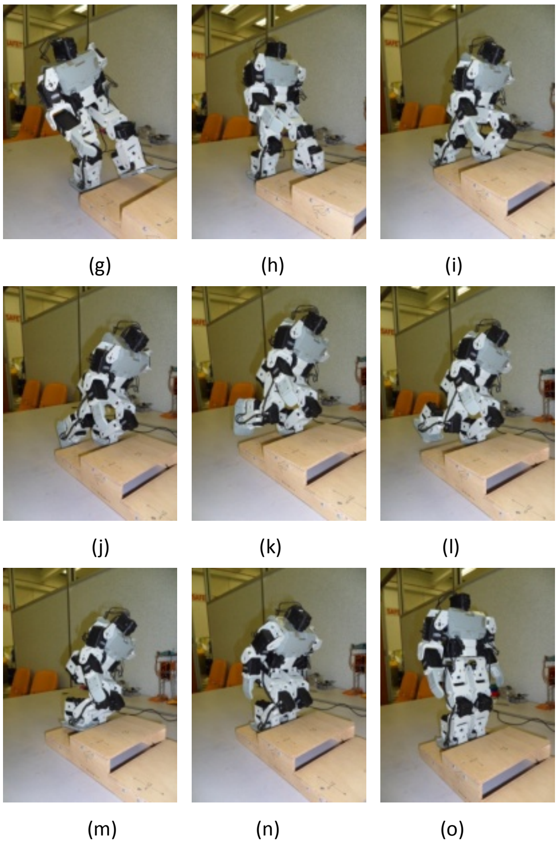


Figure 5. Various poses for step up stairs experimented using BIOLOID humanoid

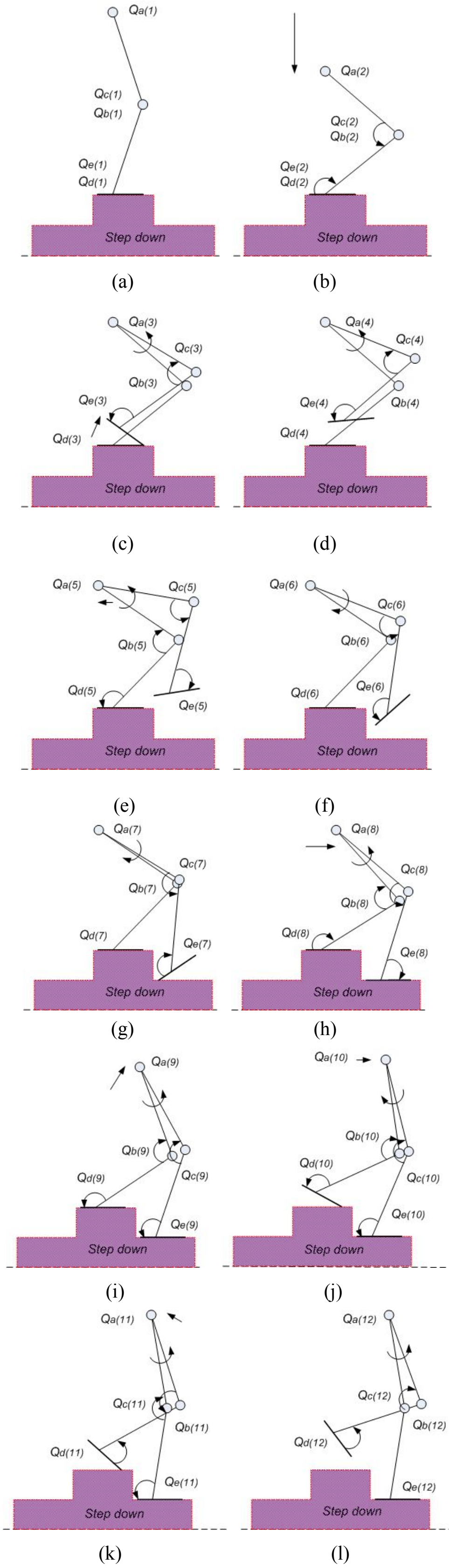
2.4. Fashion of Descending Stairs

Gait for Step down stairs is one of the critical tasks for the humanoid where total of seventeen poses are executed sequentially. After the Action Pose of this gait, the humanoid drops its CoM point downwards by bending both of the knees as shown in Figure 6 (b). After that the robot tilts to one side to start the first swing phase. The swing phase continues with three poses and ends up by touching the down step with the heel of the swing foot as shown in Figure 6 (c) to (g). During the next four poses the system moves its torso forward, upward, forward and finally a little bit backward to ensure the stability transfer from rear leg to front leg. The second swing phase starts after this action as shown in Figure 6 (k). Next five poses are performed one after another to reach at the final stage of the second swing phase, Figure 6 (p). The whole process is completed with the Action Pose of the bipedal system. Based on the general equation as represented in Equation (1) and Equation (2), the strategy is formulated as,

$$\vec{P}_{SD} = \overrightarrow{P_i P_f} = \sum_{i=1}^{f=17} f(\vec{Q}_{(i)})$$

$$= \sum_{i=1}^{f=17} f(\vec{Q}_{a(i)}, \vec{Q}_{b(i)}, \vec{Q}_{c(i)}, \vec{Q}_{d(i)}, \vec{Q}_{e(i)}) \quad (4)$$

Here $\overrightarrow{P}_{SD}$ represents the Step Down Stairs vector as the function of a set, $\overrightarrow{Q}_{(i)}$, of the joint vectors in a certain pose of the gait. The gait may start by activating any of the left or right leg. The functions, *StDN_Left ( )* and *StDN_Right ( )* is possible to define where the series of poses are executed by the system in a serial manner. Defining the main function for Step Down Stairs as *StDN ( )*, as presented in Figure 7.



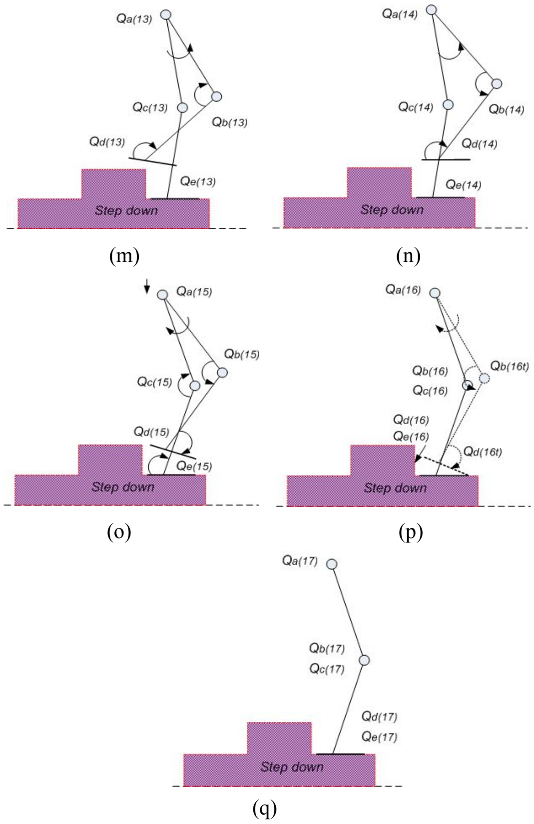
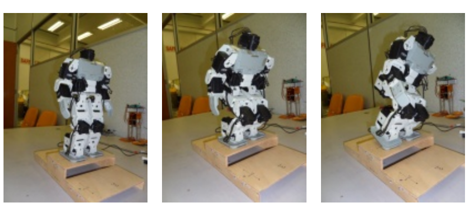


Figure 6. Seventeen various poses to perform a single step down of the stairs, (a) Action Pose, (b) CoM Drop Pose, (c) $Tilt_a$ Pose, (d) $DS\text{-}SS_a$ Pose (e) $Foot_a$ Forward Pose, (f) $Foot_a$ Adjust Pose, (g) $SS\text{-}DS_a$ Pose, (h) $SS\text{-}DS_a$ Complete Pose, (i) CoM Lifting Pose, (j) CoM Forward Pose, (k) $Tilt_b$ Pose, (l) $DS\text{-}SS_b$ Pose, (m) $Foot_b$ Forward1 Pose, (n) $Foot_b$ Forward2 Pose, (o) $Foot_b$ Adjust Pose (p) $SS\text{-}DS_b$ Pose and (q) Action Pose

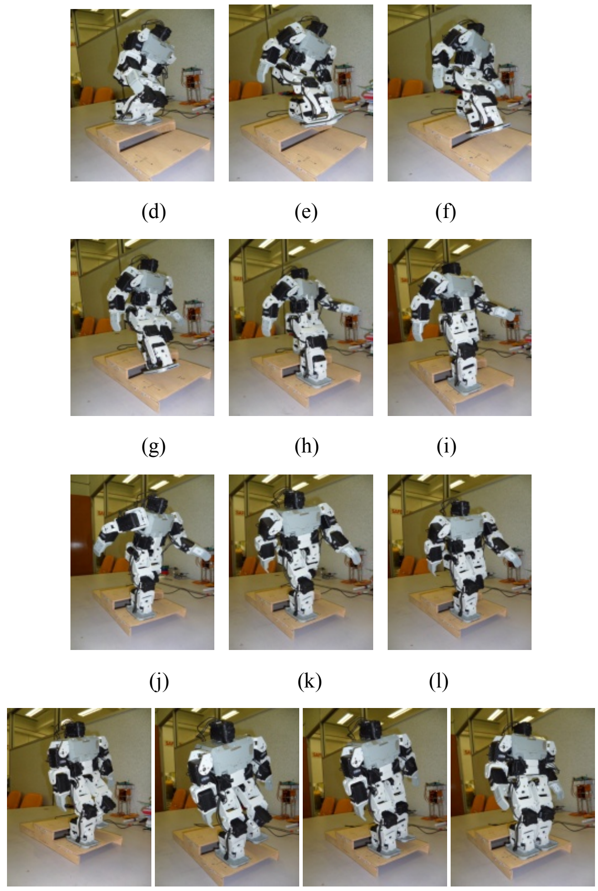
```
Declare StDN (parameter: integer i)
        If i is equal to 1
                Call StDN_Left ();
        End of if
        Elseif i is equal to 2
                Call StDN_Right ();
        End of elseif
        Return 0;
End of StDN
```

Figure 7. Defining the Step Down function as *StDN ( )* with a parameter value indicating the action leg

Figure 8, bellow, illustrates the various poses for step down stairs applied on the BIOLOID humanoid system.



(a) (b) (c)



(d) (e) (f)

(g) (h) (i)

(j) (k) (l)

(m) (n) (o) (p)

Figure 8. Various poses for step down stairs applied on BIOLOID humanoid where (p) represents the $SS\text{-}DS_b$ & Action poses

3. Joint Demeanors and Discussions

The various angular positions of the rotary joint actuators are represented in a tabulated format. All the required angular positions are calculated depending on the various poses of the various gaits where the Geometrical Analysis Technique (GAT) is imposed. The findings of the GAT strategy are experimented on the real time system where a small-scale adjustment is enforced to establish the robustness of the various gaits for the robotic platform. These adjustments are necessary because of the backlash errors of the servo actuators gear heads. Finally the table which is required for each gaits are updated, as shown in Figure 9, and fixed into the robot controller.

To observe the behaviors of the various actuators of the system, the tabulated pose angles of the different gaits are simulated in MatLab using the General Spline Interpolation method as *Spline = spapi(k , x , y)* and *fnplt(Spline)*, where the first argument in *spapi( )*, *k*, is the order of the interpolating Spline.

3.1. Analysis of Joint Behaviors

Ascending and Descending stairs are the laborious task for the biped system. In this section, the two separate gaits with different behavior of joint movement patterns are observed for the Up going and the Down going steps. The mirror joint actuator movement characteristics of the performed actions are compared by simulating the tabulated values of the designed gait patterns of the humanoid platform. Figure 10 combines the various trajectories for the Shoulder and Elbow joint actuators where the robot performs the one step up and one step down of the stairs. The rest of the figures from Figure 11 to Figure 16 express the various deflections that occur on the lower torso actuators for the same experiment.

Various Poses for Step Up Stairs																	
	Angular Values (ϴ) in Degree																
Joints	Initial Pose	Action Pose	Tilt_a Pose	DS-SS_a Pose	Foot_a Lifting	Foot_a Forward	Foot_a Adjust	SS-DS_a Pose	SS-DS_a Complete	Tilt_b Pose	CoM Lifting	DS-SS_b Pose	Foot_b Lifting	Foot_b Forward	SS-DS_b Pose	Action Pose	Initial Pose
1	46	34	46	46	46	65	65	65	65	66	66	66	66	65	34	34	46
2	186	197	186	140	186	214	222	222	207	219	219	219	219	218	197	197	186
3	53	53	53	48	48	48	48	48	47	47	47	47	47	47	53	53	53
4	179	179	179	169	169	169	169	169	172	172	172	172	172	171	179	179	179
5	116	82	116	116	116	82	82	82	81	81	81	81	81	80	82	82	116
6	116	150	116	116	116	150	150	150	137	145	145	145	145	145	150	150	116
7	116	116	116	116	116	116	116	116	114	114	114	114	114	112	116	116	116
8	116	116	116	116	116	116	116	116	113	118	114	114	114	114	116	116	116
9	116	116	125	103	103	103	103	103	118	114	115	115	115	121	116	116	116
10	116	116	125	111	116	116	116	111	116	114	116	129	129	129	116	116	116
11	116	102	102	90	90	97	102	102	101	107	98	87	83	43	43	102	116
12	116	130	130	114	152	180	182	168	161	197	189	189	189	189	189	130	116
13	116	92	92	92	92	92	92	92	91	98	98	57	45	31	38	92	116
14	116	139	139	116	180	184	161	151	133	201	194	194	194	194	194	139	116
15	118	129	129	128	128	128	128	128	134	147	107	107	159	159	150	129	118
16	114	103	103	90	88	104	104	100	138	91	82	82	82	82	82	103	114
17	116	116	125	125	124	124	124	124	121	112	106	106	106	105	113	116	116
18	116	116	125	125	127	127	127	131	119	109	107	107	107	107	112	116	116

(a) Tabulated format of the Step Up constraints.

Various Poses for Step Down Stairs																		
	Angular Values (ϴ) in Degree																	
Joints	Initial Pose	Action Pose	CoM Drop	Tilt_a Pose	DS-SS_a Pose	Foot_a Forward	Foot_a Adjust	SS-DS_a Pose	SS-DS_a Complete	CoM Lifting	CoM Forward	Tilt_b Pose	DS-SS_b Pose	Foot_b Forward_1	Foot_b Forward_2	Foot_b Adjust	SS-DS_b Pose Action Pose	Initial Pose
1	46	34	34	65	65	23	23	23	8.8	12	2.3	23	23	46	46	46	34.44	46
2	186	197	197	217	218	181	181	181	160	171	158	165	165	186	186	186	197.1	186
3	53	53	53	47	47	57	57	57	56	56	56	48	48	48	48	48	52.57	53
4	179	179	179	170	170	171	171	171	180	180	172	178	178	169	169	169	179	179
5	116	82	82	81	80	80	80	80	90	90	90	105	105	116	116	116	81.8	116
6	116	150	150	145	145	145	145	145	148	148	148	136	136	116	116	116	149.8	116
7	116	116	116	115	112	112	121	127	132	131	129	114	114	116	116	116	115.8	116
8	116	116	116	116	114	114	123	125	131	131	131	121	116	116	116	114	115.8	116
9	116	116	116	121	121	121	121	119	110	118	118	110	110	103	103	103	115.8	116
10	116	116	116	129	129	125	125	121	114	120	120	112	112	116	114	108	115.8	116
11	116	102	50	53	43	45	72	69	79	95	83	89	89	90	90	90	102	116
12	116	130	182	182	182	175	164	167	151	114	129	109	131	152	153	130	129.8	116
13	116	92	38	45	31	102	109	109	95	91	90	90	90	92	92	92	92.23	116
14	116	139	194	194	194	194	200	200	199	162	162	135	193	180	170	125	139.1	116
15	118	129	150	126	159	98	108	108	104	121	128	127	130	128	128	128	128.7	118
16	114	103	82	82	82	82	75	75	64	68	88	112	97	88	88	111	102.9	114
17	116	116	113	102	105	105	114	113	113	118	121	124	124	124	124	124	115.8	116
18	116	116	112	107	107	107	107	107	113	121	121	130	130	127	127	127	115.8	116

(b) Tabulated format of the Step Down constraints.

Figure 9. Tabulated values of the corresponding angular positions of the joint actuators for various poses of Ascending and Descending Steps

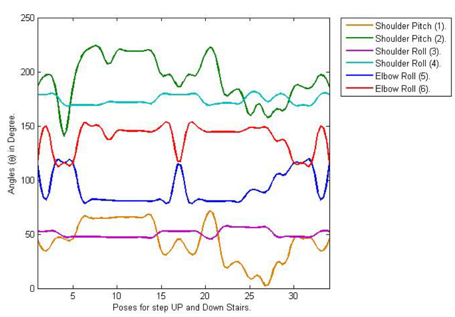


Figure 10. Upper torso mirror actuator movement patterns to execute the gaits for Step Up and Down Stairs

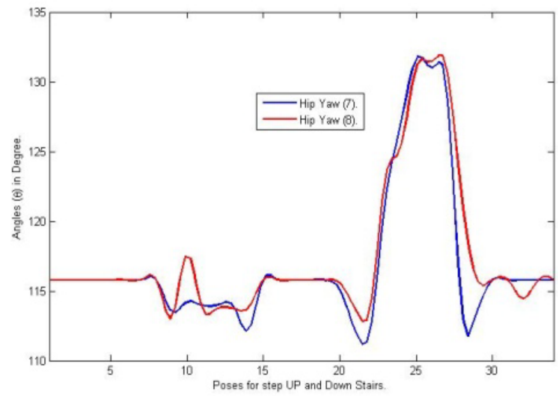


Figure 11. Motion trajectories of Hip Yaw mirror actuators while performing Up and Down Stairs

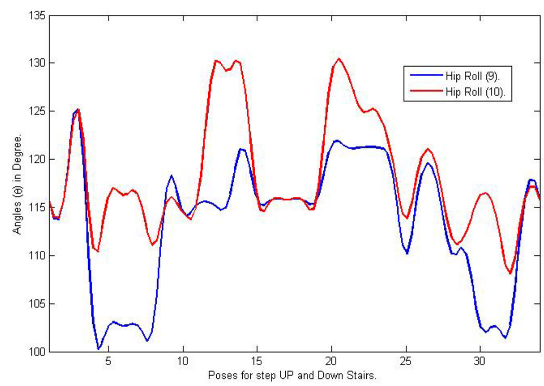


Figure 12. Motion trajectories of Hip Roll mirror actuators

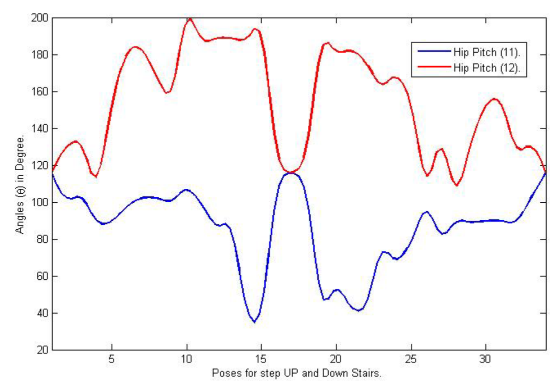


Figure 13. Motion trajectories of Hip Pitch mirror actuators

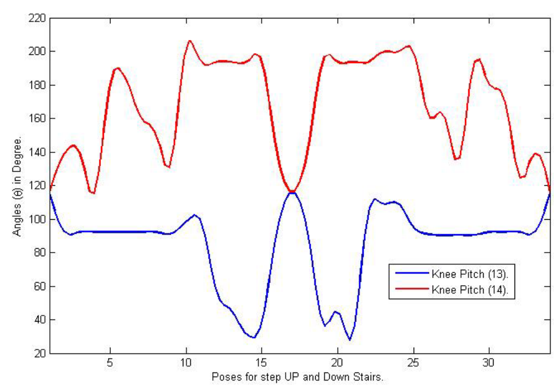


Figure 14. Motion trajectories of Knee Pitch mirror actuators

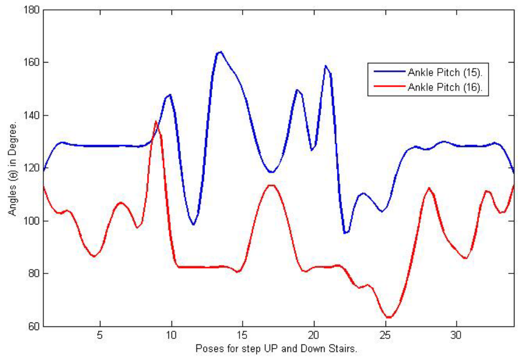


Figure 15. Motion trajectories of Ankle Pitch mirror actuators for Up and Down Steps of the Stairs

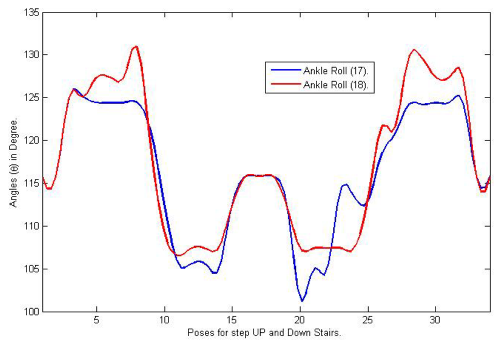


Figure 16. Actuator Motion trajectories for Ankle Roll mirror joints while stepping Up and Down Stairs

The behavior of the Hip Yaw and Ankle Roll joint actuators are showing almost same trajectory paths for their corresponding mirror actuators, indicating in Figure 11 and Figure 16. These characteristics also represents that the z-axis assignment for these joint coordinates are in the same direction. Although the motion trajectories for Hip Roll mirror actuators show a little bit diversion, Figure 12, their z-axis for local frames are also in the same direction. All the other Pitch actuators which are mounted at the lower torso of the robot present the opposite deflection characteristics for their corresponding mirror actuators because of the z-axis assignment of the joint frames are in opposite direction to each other. These characteristics are represented from Figure 13 to Figure 15. Basically these natures of the joint actuators are significant to perform the stable gait for ascending and descending steps of the stairs. The first half or the each graphs represents the pattern for stepping up stairs. The fashion of step down stairs can be expressed by the second half of the graphs, shown from Figure 10 to Figure 16.

5. Conclusions

As the experiment is a part of the main project to establish an optimal navigation system in indoor environment, the robustness of the designed gait is ensured through FK and IK analysis to identify the D-H parameters and imposing GAT or G-T formulation technique. The CoP-CoM tracking strategy is formulated based on the various patterns of the footsteps and zigzag motion of the CoP point where the CoM follows the CoP movement path. The ZMP concept is imposed to have the basic strategy of this analysis. As no sensors are used to acknowledge the environment or contact points on the ground, the CoP point is selected based on the percent of total pressure changes on the straight line between the ankle points of two legs. The percent of pressure is calculated automatically contingent upon a mathematical equation which is excogitated from the predefined step length, step angles and foot lengths. The robot performs its task to step over the stairs comparatively in slow motion but in a robust way by maintaining its torso in upright position. Basically a human like walking gait is tried to design that is experimented using the BIOLOID system and the joint movement behaviors of this robot are analyzed and presented in this paper. The experimental result shows that such kind of gait is feasible to implement on a real size humanoid robot to establish a navigation strategy in indoor environment.

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