ZMP Based Gait Generation of AIT’s Leg Exoskeleton

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Abstract—This paper proposes an approach of generating the gait pattern that Asian Institute of Technology’s Leg EXoskeleton (ALEX) and its wearer can walk safely with the passing criteria of Zero Moment Point (ZMP) theorem for static and dynamic considerations, respectively. ALEX has 12 DOF (6 DOF for each leg: 3 at the Hip, 1 at the knee and 2 at the ankle), controlled by 12 DC motors. The CAD drawing and assembly of ALEX are exported directly to MATLAB’s Simulink/SimMechanics simulation environment to assure accurate positioning of center of gravity (CG) and moment of inertia of each of the links that make up this 12 DOF robot. The gait pattern is visually observed in virtual environment (VR) using 3D VRML interpreter while ZMP trajectory is monitored using MATLAB’s 2D graphics representation. With this developed simulation of ALEX, the robot can be tested to confirm its balance gait motion prior to the real implementation on the physical system that could cause serious damages to the robot itself and its fragile electronic devices.

Keywords—ALEX; Exoskeleton; Gait generation; Zero Moment Point (ZMP).

I. INTRODUCTION

Robotic exoskeletons systems find its applications in various fields that draw a lot of interests from many researchers who want to imitate the perfectly designed and sophisticated biomechanics and human anthropometries. The exoskeletons are developed to help humans in performing tasks that they would normally have difficulties with due to either their physical limitations or muscles’ fatigue. In addition, exoskeletons can also help increasing the endurance, speed of traveling, and even balancing the wearer in extremely difficult terrains.

The 21st century has seen resurrection in exoskeleton investigation. In Japan, the Tsukuba University developed the lightweight power assist device, Hybrid Assistive Limb (HAL), [1,2]. This exoskeleton has a portable power supply, but only assists the operator’s leg muscles; it cannot carry an external load. HAL is a full-body suit designed to aid people who have degenerated muscles and paralyzed from brain or spinal injuries. University of California at Berkeley, for example, develops their robotic exoskeleton, BLEEX, primarily for military purposes. BLEEX is a field-operational robotic system which is worn by an operator and provides him/her ability to undertake significant loads on the back with minimal effort while navigating any terrains [3]. BLEEX has seven DOF per leg and highly maneuverable, mechanically robust, lightweight and durable. The Clinical Gait Analysis (CGA) Data was used to determine the joint power requirement for the human-machine system [4]. This CGA helps eliminating unnecessary joints from the seven DOF of each leg to be actuated.

Optimal gait trajectories are considered to help smoothening the locomotion, increasing the accuracy of the positioning of feet and body posture, and optimizing the mechanical efficiency to save energy for the walking task. Many researchers, a planed trajectory for robots to follow relies on CGA data. The more popular approach is using the Zero Moment Point (ZMP). ZMP based approach largely relies on the precise knowledge of robot dynamics including mass, location of center of mass (COM) and inertia of each link to prepare the walking pattern [5]. ASIMO by Honda has used six-axis force sensors in each foot of the robot to detect ZMP [6]. In addition to this, ASIMO uses accelerometers and inclinometers to measure the overall orientation of the robot.

The objective of this paper is to determine the offline gait pattern for the developed exoskeleton that are statically and dynamically stable according to the ZMP criteria through the simulation modeling approach employing the MATLAB’s Simulink/SimMechanics toolbox. This research will contribute to the ease of finding the feasible joint trajectories for the desired walking parameters link the step size, step time, and body posture. These feasible joint trajectories are basically the angle profiles of all the joints that the robot should go through in order to walk according without tipping over or going over its designed constraints.
Section 2 briefly explained ALEX’s system; both mechanical hardware and simulation model. The gait generation is highlighted in section 3. Section 4 shows simulation and results of gait pattern analysis. Finally, conclusions are made in section 5.

II. ALEX

ALEX has 12 DOF (6 DOF on each leg: 3 at the hip, 1 at the knee and 2 at the ankle), controlled by 12 DC motors. Each motor is coupled with a 1:100 gearhead and equipped with a 1024-pulse per revolution incremental encoder as a feedback sensor. The DC motors and Gearhead from Bonfiglioli model VF44P63B14 are used. PCI04 and ARM7 are basically used as high level and low level controllers respectively. The lower limb exoskeleton mechanical structure is designed by a CAD software, SolidWorks. Aluminium 5083 with the density of 2657.27 Kg/m$^3$ is mainly used for the frame structure. The CAD drawing and prototype of ALEX is shown in Fig. 1. The weight of the ALEX is measured about 117.5 Kg excluding the weight of the backpack.

Aphiratsakun has been previously explained how the simulation model of ALEX been created [7]. The SolidWorks CAD drawing is then imported to MATLAB Simulink/SimMechanics environment, which will is used to analyze the balanced gait motion through the simulation model. Apparently, this simulation model is very accurate in resembling the real physical exoskeleton as it is created from the exact sizes, mass and inertia properties, and joint locations of the real fabricated links and assembles robot. With this physical model, the virtual actuation of all joints are possible as well as the visualization of resulting movement of the robot in Virtual Reality (VR) environment. Fig. 2 shows the flow of the precise simulation model from the CAD data.

![Prototype](image)

Figure 1. ALEX Model (a) SolidWork Design, and (b) Prototype.

![Simulation Model](image)

Figure 2. ALEX’s Simulation Model.

<table>
<thead>
<tr>
<th>Parts</th>
<th>Segment Mass (kg)</th>
<th>Moment of Inertia (kg-m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot</td>
<td>0.0145M = 0.9425</td>
<td>-</td>
</tr>
<tr>
<td>Shank (leg)</td>
<td>0.0465M = 3.0225</td>
<td>-</td>
</tr>
<tr>
<td>Thigh</td>
<td>0.1M = 6.5</td>
<td>-</td>
</tr>
<tr>
<td>HAT (head + arm + torso)</td>
<td>0.678M = 44.07</td>
<td>0.527 0.447 0.671</td>
</tr>
</tbody>
</table>

ALEX has been designed and developed with the aim to carry a wearer, therefore wearer’s model is considered and added to the model. ALEX is designed for 65 kg and 1.71 m wearer. The mass of the feet, shanks, and thighs of the wearer are added directly to each link of ALEX in the simulation model. However, their moments of inertia are neglected since they are quite small compared to the moment of inertia of the aluminium frame. The mass and moment of inertia of head, arms and torso (HAT) of the wearer are determined and included in the simulation model. The approximated mass and inertia of each part of the wearer is shown in Table I.

III. GAIT GENERATION

This section explained how to generate geometrically possible postures as the joints and links may allow and how to pick only ZMP feasible postures among all postures for further development of desired locomotion.

A. Gait Motion Trajectory and Its Interpolation

The gait cycle of ALEX-I based on ZMP criteria is determined and generated by SimMechanics Library in MATLAB. The entire ZMP trajectories of a particular locomotion pattern can be computed by (1)-(3). The resulting trajectories of ZMP would prevent the exoskeleton from tipping over both in sagittal plane and frontal plane.

$$x_{ZMP} = \frac{\sum m_i (\ddot{y} + g) x_i - \sum m_i \ddot{x}_i - \sum I_{\theta} \ddot{\theta}}{\sum m_i (\ddot{y} + g)}$$

(1)
Rebecca applied polynomial curve fitting to the gait data to obtain smooth walking motion of a biped robot [8]. ALEX also applies the polynomial curve fitting to generate the gait motion trajectory. A polynomial function is characterized by \( n+1 \) coefficients.

\[
P_i(x) = p_1 x^n + p_2 x^{n-1} + \ldots + p_n x + p_{n+1}.
\]

In this work, \( n = 2 \) is selected and the polynomial function becomes

\[
P_i(x) = p_1 x^2 + p_2 x + p_3.
\]

In the interpolation when \( x_0 < x < x_1 \) with the corresponding function values \( y_0 < y < y_2 \), the equation used in the interpolation is

\[
\begin{bmatrix}
y_0 \\
y_1 \\
y_2
\end{bmatrix} =
\begin{bmatrix}
x_0^2 & x_0 & 1 \\
x_1^2 & x_1 & 1 \\
x_2^2 & x_2 & 1
\end{bmatrix}
\begin{bmatrix}
p_1 \\
p_2 \\
p_3
\end{bmatrix}.
\]

**B. Gait Pattern Selection**

ALEX is developed based on the idea of assuming it as the robot manipulator having one of the foot based on the ground and another foot swinging with the twelve joint trajectories assuming it is the end effector. Obviously, all of the joints angles would be moving back and forth between their two extreme values just like the sine and cosine curves. Therefore, simulation of all possible motions can be achieved using just sine curves with frequencies reducing every time it moves to the next adjacent joint. Using basic sine formulation and step size of the increment or decrement is limited to minimum of five degree per one step of changes in joint motion. All joints motions were created with detail indicated in Table II.

**C. Filtered ZMP Feasible Gait Generation**

Evidently, not all the postures created by method described in the previous section would be stable according to criteria of ZMP. A programming code is written to solve the problem of filtering out the nonstable posture. With random sampling from all postures \( 6.1 \times 10^9 \) postures) while arranging them from time 0 second to \( 6.1 \times 10^9 \) seconds, the range of time (searching domain) that returns stable leg-swinging postures could be found from Fig. 4(a) between \( 4.18 \times 10^9 \) to \( 5.91 \times 10^9 \) seconds. From the sampled experiment, the authors could reduce size of the searching domain from \( 6.1 \times 10^9 \) solutions to approximately \( 2 \times 10^9 \) solutions. However, from the visual interpretation in VR environment, the postures that result from the solution numbered \( 4.7 \times 10^9 \) to \( 5.91 \times 10^9 \) show the waist orientation that would be difficult for the wearer of the exoskeleton to move along with the exoskeleton. Therefore, another detail simulation is performed to determine the ZMP-feasible postures (joint angles) within the searching domain \( 4.18 \times 10^9 \) to \( 4.7 \times 10^9 \). The result is shown in Fig. 4(b).
Initially the walking cycle starts when the left leg is behind the supported left foot, and then the right swing is started. The walking cycle ends when the right swing is completed. The COM to the supported right foot and then starts left swing. At this stage, the body COM is then shifted back to the initial and final locations of the swung feet.

Only the postures (joints angles) that return the balanced gait are saved into the database so that the interpolation of all feasible joints angles could be interpolated. The filtered postures are again interpolated to obtain very detailed joint trajectories and filtered to get only the balanced ZMP joints angles. The resulting filtered ZMP locations are shown Fig. 5.

With the feasible joint trajectories, the step parameters, which comprise the swinging height, step length, and step time, are obtained. After having all joints angles in the database together with the location of the swing foot and orientation of the ALEX from the virtual sensors in the simulation model, the one-step gait pattern is generated from the ZMP-feasible joint trajectories.

IV. SIMULATION AND RESULTS

This section shows the simulation and results of generated gait motions of ALEX. This gait pattern is generated in MATLAB with Simulink/SimMechanics library. Initially the walking cycle starts when the left leg is behind the right leg. ALEX then moves the body center of mass (COM) to the supported right foot and then starts left swing. At this stage, the body COM is then shifted back to the supported left foot, and then the right swing is started. The walking cycle ends when the right swing is completed. The walking gait cycle of ALEX is generated and gaits data of twelve joints are shown in Fig. 6. Fig. 7 revealed the ZMP of the gait cycle of a single step.

The successful one-step animations are shown in Fig. 8 with the outline initial and final locations of the swung feet. The step parameter is 30 cm forward along [Z] direction and 15 cm up along [Y] direction. Stability of ALEX is proven by ZMP always lied in the convex hull region.

Figure 4. (a) Location of ZMP sampled over the entire searching domain, and (b) Location of ZMP sampled over the reduced searching domain.

Figure 5. Filter and interpolated feasible posture ZMP-save joints.

Figure 6. One Step Gait Cycle data.

Figure 7. ZMP Reference for One Step Gait Cycle.

Figure 8. Simulation of Gait Pattern for One Step Gait Cycle.
V. CONCLUSION

This research proposes an approach in tackling the problem of determination of the offline safe gait motion for the developed Asian Institute of Technology’s Leg EXoskeleton (ALEX). In this work, authors have shown how precise modeling of fabricated exoskeleton frame and joints could be done by exporting the SolidWorks assembly files into MATLAB Simulink/SimMechanics. This method allows the irregular geometries of the real ALEX’s links to be described with accurate inertia tensors and location of center of gravity. The authors also have illustrated how ‘safe’ locomotion were filtered and generated from all geometrically feasible postures, whose ranges of motion of all joints are covered. This stability postures are defined by criteria of ZMP of which the error compensated stable region is served as a safety factor for any calculation error and kinematics characteristics that is unintentionally missed during the modeling phase.

The simulation proves visually, with 3D VR interpreter and MATLAB’s 2D graphics, and numerically that the walking parameters such as swinging height, step size, and step pace could be specified in this approach of gait generation. Thus, the ALEX is proven to be capable of walking on plane ground.

The research shows promising results as well as potentials in applying the same methodologies on other simpler mechanism for the determination of any kinematics characteristics and confirming the controllability of the system. The future works would emphasize on the implementation with the real wearer, and disturbance-tolerating control system.

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