Generate an optimum lightweight legs structure design based on critical posture in A-FLoW Humanoid Robot

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Abstract. Lightweight construction and energy efficiency play an important role in humanoid robot development. The application of computer-aided engineering (CAE) in the development process is one of the possibilities to achieve the appropriate reduction of the weight. This paper describes a method to generate an optimum lightweight legs structure design based on critical posture during walking locomotion in A-FLoW Humanoid robot. The critical posture can be obtained from the highest forces and moments in each joint of the robot body during walking locomotion. From the finite element analysis (FEA) result can be realized leg structure design of A-FLoW humanoid robot with a maximum displacement value of 0.05 mm and weight reduction about 0.598 Kg from the thigh structure and a maximum displacement value of 0.13 mm and weight reduction about 0.57 kg from the shin structure.

1. Introduction
Research in the field of robotics grows rapidly, one of them is a humanoid robot. Humanoid robots are human-like robots, many researchers have successfully developed humanoid robots such as ATLAS [1], WABIAN [2], HUBO [3], LOLA [4] and ASIMO [5]. In previous research, EEPIS Robotic Research Centre (ER2C) laboratory has developed adult-sized humanoid robot named A-FloW[6]. This robot was developed using parallel link mechanism with 24 servo motors and 4 linear motors. Too many motor and mechanical parts increase the weight of robot to 25 kg in lower robot design. In order to reduce the weight, the robot will be redesigned using serial link mechanism. Computer-aided design (CAD) offers a wide variety of function that facilitates a design process. Traditional CAD systems primarily support modeling and analysis of conceptual solutions [7]. However, these systems rely on the user to interpret their design problems and create conceptual solutions on their own. The systems do not actually explore and provide solution for users [8]. Generative design method will be used to reduce the mechanical weight in this research. In this generative design method forces and moment are used as input in simulation to generate structure based on the distribution of the strain and stress [9,10]. There are three stages to design leg structure of A-FLoW humanoid robot as shown in figure 1.

Figure 1. The design process of humanoid robot structure FLoW2.
The first stage is to define the humanoid robot form, the jointtype, and the mechanism. Then in the second stage, the kinematics of the robot is made. After that, a dynamic simulation is executed to find the value of force and moment that work on every joint. The highest value of force and moment in the quasi-dynamic simulation used as input in the generative design process at the final stage [11].

2. Kinematic Modelling

2.1. Inverse kinematics
This section describes the model of inverse kinematics in A-FLoW humanoid robot. This work has been solved in previous research in T-FLoW humanoid robot [12]. So, can be obtained the inverse kinematics in Equation 1-3.

\[ \theta_1 = Orientation \]
\[ \theta_2 = \tan^{-1}\left(\frac{\sqrt{x^2+y^2}+\sin(\tan^{-1}(y/x)-0)}{z}\right); \theta_6 = \theta_2 \]
\[ \theta_3 = \sin^{-1}\left(\frac{\sqrt{x^2+y^2}}{r_1^2+a}\right); \theta_4 = \pi - \sin^{-1}\left(\frac{l_2\sin(\theta_{oa})}{r_1^2+a}\right); \theta_5 = \theta_3 + \theta_4 \]

Where \( \theta_1, \theta_2, \theta_3 \) are hip yaw, roll, pitch, \( \theta_4 \) is knee pitch and \( \theta_5, \theta_6 \) are ankle pitch, roll. There are three planes to solve this inverse kinematic model. Where Equation 1 is in transversal plane, Equation 2 is in frontal plane and Equation 3 is in sagittal plane. The angle calculation at each joint of the leg will be used as input parameters in quasi-dynamic simulation using Autodesk Inventor.

2.2. Walking Strategy
Walking strategy is needed to find critical posture and step conditions in single support phase (SSP) and Double Support Phase (DSP). Walking strategy is used to organize trajectory on the cartesian coordinate system (x, y, z-axis). This walking strategy has been solved in the previous research [13]. Then can be obtained the walking strategy in Equation 4-7.

\[ \Delta S_{LT,RT}(x,y,z),(i) = PP_{LT,RT}(x,y,z),(i+1) - PP_{LT,RT}(x,y,z),(i) \]
\[ X_{LT,RT}(T_m+T_{mn}) = \left(-\cos(T_T+T_{mn}) + 1\right) \times \Delta S_{LT,RT},x,(i) + PP_{LT,RT},x,(i) \]
\[ (Y,Z)_{LT,RT,(1,2,4,5),(T_m+T_{mn})} = \left(\sin(T_T+T_{mn}) \times \Delta S_{LT,RT},(y,z),(i)\right) \times PP_{LT,RT},(y,z),(i) \]
\[ (Y,Z)_{LT,RT,(3,6),(T_m+T_{mn})} = \left(1 - \sin(T_T+T_{mn}) + 90\right) \times \Delta S_{LT,RT},(y,z),(i) \]
\[ +PP_{LT,RT},(y,z),(i) \]

Where LT indicate left leg and RT indicate right leg. x, y, and z are walking trajectory parameter in cartesian. Then i is the number of steps while the robot walking. Equation 4 used to calculate the distance between apresent point and the last point parameters. Equation 5 is used to obtain trajectory generator in the x-axis (step 1 to 6) and Equation 6 and Equation 7 used to obtain trajectory generator in y,z-axis. Equation 6 is in rising and transition step but Equation 10 is in landing step.

2.3. Critical Posture
Critical posture is a condition in which the movement of the foot structure of the robot holds the highest load that may occur when the robot is walking. Critical posture is derived from a simulation of walking motion on A-FLoW robot.
When the walking motion implemented in the free-body diagram in Figure 2. Then trajectory of walking can be generated as shown in Figure 3. From the kinematic simulation, the angle in each joint of the leg can be obtained. Those resulting angle shown in Figure 4 are what will be used as input parameters in the quasi-dynamic simulation.

3. Generative Design Implementation

3.1. Quasi-Dynamic Load Analysis

In the dynamic simulation, the balancing control on the robot is not applied. The input parameters for the robot motion in the dynamic simulation is generated from the inverse kinematic calculated on MATLAB. So, in the dynamic simulation, the robot can walk with a predetermined trajectory.

Quasi-dynamic load analysis is used to simplify the dynamic model of the robot. The motion simulation in Autodesk Inventor is captured only in the peak value of SSP condition without losing its inertial effects as shown in Figure 5. So, the highest moments work on each leg joint will be obtained as displayed in Figure 6.

3.2. Shape Generator

Shape Generator provides an intelligent strategy for maximizing part stiffness based on the constraints that have been specified [9,10]. Shape Generator produces a 3D mesh that can be used to guide the design refinement. The technology of shape generator integrated into some CAD software. The Autodesk fusion 360 used in this research make the design process more convenient to incorporate.
The distribution of stress on the thigh and shin structure after the load given to the structure are shown in Figure 7. The distribution of the most stress in the structure is indicated by the red area in the structure. So, the area is avoided to be removed in the load reduction process, Figure 8 shows the load reduction process by removing the blue area which gets the least stress and strain distribution.

4. Experiment and Analysis

4.1. Design Optimization Process
In the design optimization process of leg structure in A-FLoW humanoid robot, the conventional method is also presented using iterative design process as described by A. Albers in his research [8]. The conventional method will be compared to the proposed generative design method. So, it can be calculated the weight reduction from the conventional method to generative design method.

The design optimization process is displayed in Figure 9. The weight from the conventional design of thigh structure is 1.703 kg, after redesign using generative design method the weight of the thigh structure reach 1.179 kg and the final weight of produced part become 1.105 kg.

Figure 7. The distribution of stress and strain on thigh and shin structure.

Figure 8. Weight reduction on the structure of shin based on the stress and strain distribution.
Figure 10. The comparison of weight in shin design optimization process between conventional design processes, optimization result, redesign process and the manufactured part.

The design optimization process is displayed in Figure 10. The weight of the conventional design of shin structure is 1.582 kg, after redesign using generative design method the weight of the thigh structure reach 1.149 kg and the final weight of produced part become 1.012 kg.

4.2. Design Analysis
In design analysis, Finite Element Analysis (FEA) method is presented. FEA shows whether a product will break, wear out, or work the way it was designed. EA works by breaking down a real object into a larger number of finite elements, such as little cubes. A computer then adds up all individual behaviors to predict the behavior of the actual object.

Figure 11. The FEA method is used in structural analysis on the design of the thigh.

The material used in the analysis is aluminum 7075. The analysis in Figure 11-12 shows the strain and stress spread evenly on the generated structure. The structure is analyzed by the loading of critical posture on the robot. The maximum stress and displacement in the thigh structure are 4.86 MPa and 0.05 mm. The maximum stress and displacement in the shin structure are 15.04 MPa and 0.13 mm.

4.3. Manufacturing Result
The manufactured part will be presented in this section. Designed structure in the previous stage will be disassembled into some part both in the thigh and shin structure. The raw material used to build each part is aluminum plat 7000 series. With the various thickness are 5 mm, 8 mm and 12 mm. Then the parts are manufactured using 3-axis CNC machine.
5. Conclusion
The main result of the experiment is a reduction of leg structure design using generative design method compared to conventional method. The weight reduction is 0.598 kg in the thigh structure with the maximum stress and displacement from the thigh structure are 4.88 MPa and 0.05 mm. The weight reduction is 0.57 kg from the shin structure with the maximum stress and displacement are 15.04 MPa and 0.13 mm. The total weight is 16.14 kg in both of leg after the actuator has assembled, it finds out that the new leg design of A-FLoW humanoid robot more lightweight than its previous model.

But new problems appear in this research. The problem is the value of weight reduction is also based on the manufacturing constraints. So, the redesigned model can’t fully meet the generated shape proposed by the generative design method. By the appeared of new problems, the next research will be a focus on manufacturing generative design using a metal 3D printer. So, the weight of the structure can be optimized more by having flexibility geometric shape and removing bolt connector.

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Acknowledgments
Gratefulness to Ministry of Research, Technology and Higher Education of the Republic of Indonesia for financial support and EEPIS Robotics Research Centre (ER2C) laboratory.