Dynamics of Legged Walking Mechanism "Wind Beast"

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Summary

To optimize Mr. Theo Jansen's leg mechanism "Wind Beast" [1,2], the analyses of kinematics and inverse dynamics of the mechanism are needed. Such analyses are tedious due to the complexity of the mechanism. More importantly, the system is indeterminate, i.e., there are more unknown forces and torques than the dynamic equations. In order to perform the dynamic analysis, certain assumptions of the reactions between the foot and the ground are made based on the results of kinematics analysis.

Introduction

Many legged robots have an open-loop structure. The dynamics of these types of robots are readily derived and as a result generic equations have been developed that aids in the derivation of their dynamics. Theo Jansen's leg mechanism in "Wind Beast" is of a closed-loop form, and a new dynamics analysis needs to be performed, which results in an indeterminate system. Some assumptions for the force reactions between the foot and the ground are made. As a result all the force reactions at the joints as well as the actuating torque applied to the input crank can be determined. With the dynamic solution the optimization process can be carried out as discussed in [2].

Methods

For the mechanism shown in Figure 1, Z_1 is the frame, Z_2 is the input link, where a torque is applied, and coupler $Z_{10}Z_{11}Z_{12}$ is equivalent to a foot. The detailed design is discussed in [2]. Given the link lengths, dynamic parameters and the input link kinematics, the inverse dynamics can be analyzed for each link. The derivation of the dynamic equations is performed with the superposition method [3] where the derived equations are linear in the inertia forces. Therefore, the leg mechanism is broken down into individual free body diagrams for each link and then superimposed to represent the total system. The derivation results in 21 equations with 23 unknowns, where two of the unknowns are the horizontal and vertical reactions between the foot and the ground. As a result an assumption is made to replicate these foot reactions. With the knowledge of the kinematics it is possible to find the horizontal component of the foot acceleration with respect to the frame. Then we estimate the horizontal force as the one needed to accelerate the entire leg mechanism forward at the same acceleration of the foot. Since in this work, the leg mechanism is supported by a frame (Z_1) where the foot slides on the ground, we can estimate the vertical force required for the desired friction to counteract the horizontal force of the foot.

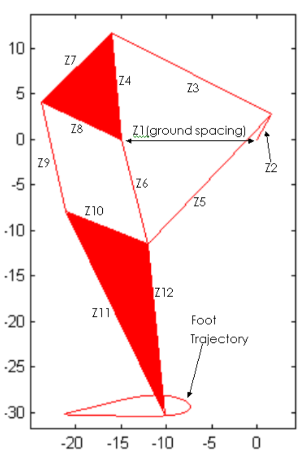

Figure 1: Foot trajectory and link numbers

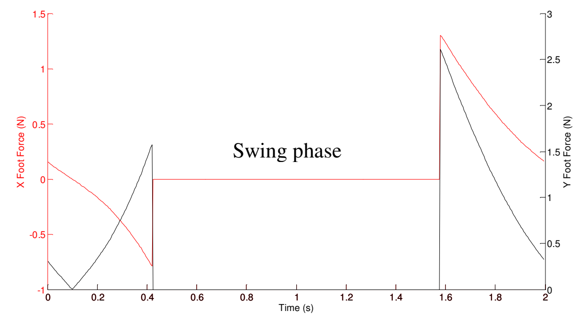

Figure 2: Horizontal (X) and vertical (Y) foot reaction forces

Results and Discussion

With the assumption of the foot reactions on the ground, the complete dynamic analysis was performed over the entire cycle. The solution returned the reaction forces at each joint and the input torque acting on the input link. As a result Figures 2 and 3 show the foot reactions and the input torque vs. time. As a result with the dynamic solution, an optimization can be performed to obtain the optimized leg mechanism as discussed in details in [2].

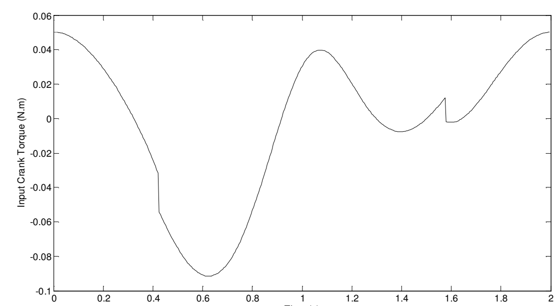

Figure 3: Input Crank Torque vs. Time

References

[1] http://www.strandbeest.com/

[2] D. Giesbrecht, C.Q. Wu and N. Sepehri, Synthesis of a Legged Walking Mechanism "Wind Beast" using Theory of Mechanism Design, submitted to *Dynamic Walking 2009, submission NO. 77.*

[3] A.G. Erdman and G.N. Sandor, *MECHANISM DESIGN -Analysis and Synthesis*, 3rd Ed, New Jersey: Prentice Hall, 1997

Table 1: Leg mechanism important data

Total mass of the leg (kg)	Max acceleration of the foot (cm/s^2)	Friction Coefficient
1.083	60.21	0.5

Synthesis of a Legged Walking Mechanism “Wind Beast” using Theory of Mechanism Design

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Summary

The kinetic sculpture, “Wind Beast” [1] created by Mr. Theo Jansen, is a multi-legged walking mechanism and each leg is a close-loop kinematic chain with one degree of freedom. In this work, we redesign “Wind Beast” using the mechanism design theory, where the free choices, required to determine the lengths of the links, are firstly obtained by trial and error to obtain the desired motion. Next, we optimize the design by reducing the energy input while keeping the desired motion. Results show that as compared with the leg designed based on trial and error, the energy input required for the optimized leg is reduced by 56%, while the traveling distance of the foot (the tracer point) per step is increased by 3% and smooth leg motion is obtained. Currently, we are in progress building a prototype of a simplified “Wind Beast”.

Introduction

Most legs in legged robots consist of a series of links, where the walking motion is controlled by motors attached at multiple if not all the joints. This can complicate the system with the necessity to apply control to each link. It has been demonstrated by the kinetic sculptor Mr. Jansen through his “Wind Beast” that a closed-loop mechanism that is actuated at a single joint can be successful at walking, thus simplifying the control system. The objective of this work is to design a leg of “Wind Beast” using the mechanism design theory. Furthermore, an optimization process is applied to reduce the energy input while maintaining the desired walking motion.

Methods

The leg is synthesized using the theory of mechanism design. We use the same type of mechanism as “Wind Beast”, *i.e.,* the mechanism consists of 8 links as shown in Figure 1. The design criteria considered are: (1) the minimum foot travel distance on the ground is 10cm for each step; (2) during the swing phase, the foot is always above the ground *i.e*., the vertical coordinate of the foot is positive and (3) during the supporting phase, the foot is always in contact with the ground, i.e. the vertical ground reaction force is positive. The design is performed in two parts: (i) the synthesis of a four-bar crank-rocker function generator with Z_1 as the ground, Z_2 as the input link, Z_3 as the coupler and Z_4 as the output link (Figure 1). Three precision points are considered and Freudenstein’s method [2] is used, and (ii) the synthesis of a path generator with Z_6 as the side link and Z_{12} as the coupler. Four precision points are considered. The parallelogram ($Z_6Z_8Z_9Z_{10}$) is synthesized to ensure the desired walking motion. The free choices are selected by trial and error.

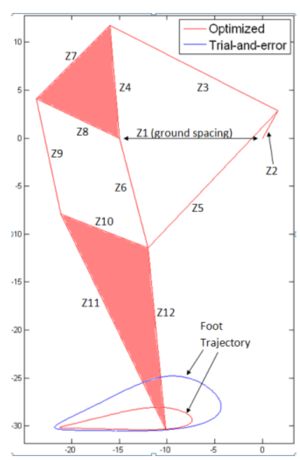
Due to limited power source, the mechanism is further optimized by minimizing the cost function as below:

$$Cost\ function = \frac{1}{L}\int_0^{\tau} T^2 dt + C_{ij}$$

where T is the torque applied to the input link (Z_2), L is the foot traveling distance per step, τ is the step period and C_{ij} are the constraints where “i (i=1,2,3)” corresponds to the three constraints discussed before, “j (j=1,2)” and as “j=1” indicating that the constraint is satisfied, otherwise, the constraint is violated. In the optimization, we have:

$$C_{ij} = \begin{cases} 0 & j=1 \\ 10 & j=2 \end{cases}$$

In order to optimize the design, two programs have been developed for the kinematic analysis (given the motion of the input link, determining the kinematics of the entire linkage) and inverse dynamic analysis (given the kinematics and dynamic parameters, determining the forces, especially the required torque for actuating the linkage). The Matlab optimization toolbox is used to manipulate the lengths of some links to minimize the cost function.



Results and Discussion

Two legs were designed. One was by trial and error, and another one was optimized based on the first leg. After 330 iterations, a convergence of 10^{-6} difference in the cost function was achieved. The length of each link is shown in Table 1 and the optimized leg and the foot trajectories from both designs are shown in Figure 1. Comparing the two leg-mechanisms, the cost function for the optimized leg was decreased by 57.6%. The energy input over the cycle was decreased by 56% while the step length was increased by 3%.

Currently we are in progress building a prototype of a simplified “Wind Beast”.

References

[1] http://www.strandbeest.com/

[2] A. G. Erdman and G. N. Sandor, *MECHANISM DESIGN - Analysis and Synthesis*, Third Edition, New Jersey: Prentice Hall, 1997

Table 1: Link lengths of the leg mechanism

Link Number	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11	Z12
Trial-and-error(cm)	15	4.17	20.33	12	20.33	12	11.14	10	11.89	10	26.11	19
Optimized(cm)	15	3.29	19.76	11.8	19.76	11.82	10.89	9.66	12.31	9.77	24.96	18.99