MODELING AND MBD SIMULATION OF STAIR CLIMBING ROBOT WITH ROCKER BOGIE MECHANISM

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Abstract: - The research paper deals with the designing and modeling of stair climbing robot based on the well-known rocker bogie mechanism in Ansys rigid body dynamics module. The robots often suffer from undesired phenomenon slip, sticking and floating while climbing steps and stairs, which may cause instability of the mobile robot. It is important to note that trajectory of center of mass serve as a tool for effectively predicting such undesirable phenomenon which is likely to occur at the moment the trajectory of center of mass drastically or discontinuously changes. Therefore it is highly required to make trajectory of center of mass as smooth as possible which implies trajectory of center of mass must be close to a straight line whose slope is determined by slope of stair or step. The Taguchi method is used to chosen as an optimization tool to make trajectory of center of mass close to straight line while all wheels keep in contact with ground during climbing stairs. Taguchi method is adopted due to its simplicity and cost effectiveness both in formulating the objective function and satisfying multiple constraints simultaneously. In the Optimization, Seven kinematic parameters of rocker bogie mechanism are optimized which include four link lengths (l₁, l₂, l₃) and three wheel radius (R₁, R₂, R₃). The kinematic Model of proposed mechanism is built and it is simulated in ANSYS Rigid body dynamics. Three different shapes of typical stairs are selected as user conditions to determine a robust optimal solution. The result shows the variation of center of mass position with time, variation of velocity of joint with time, variation of force with time.

Index Terms - rocker bogie mechanism, optimal kinematic design, Taguchi method, stair climbing robot. Ansys Rigid body dynamics

1. Introduction

Over the last decade, mobile robots have been widely used to carry out manifold tasks such as military/industrial applications, planetary exploration, rescue operation and home/medical services. Therefore, it is not surprising that high mobility on various environments has been a primary factor among others when evaluating the performance of the mobile robot. According to a locomotive mechanism to achieve the desired mobility, mobile robots may be split into following categories: leg-type, track-type and wheel-type mobile robots. While the leg-type mobile robot ensures the most superior adaptability to all kinds of environments, its mechanism is quite complicated because active control algorithms equipped with additional actuators and sensors are required to steadily maintain its balance, which inevitably leads to slow movement and poor energy efficiency. The track-type mobile robot provides acceptable mobility on an off-road environment by virtue of its inherently stable mechanism but excessive friction loss during changing a direction also results in poor energy efficiency. The track-type mobile robot provides acceptable mobility on an off-road environment by virtue of its inherently stable mechanism but excessive friction loss during changing a direction also results in poor energy efficiency. Compared to other alternatives, the wheel-type mobile robot can be constructed in the simplest configuration so that fast movement as well as good energy efficiency are guaranteed without any complicated control strategy. However, its adaptability to an environment does not seem to be sufficiently good and its mobility is restricted depending on both the type and the size of encountered obstacle. Recently, hybrid-type mobile robots have been suggested in various configurations by combining two locomotive mechanisms together.
However, their mechanisms still seem to be complicated in comparison with the wheel-type one and from the viewpoint of control, the cooperation between locomotion mechanisms emerges as another important issue. On the other hand, several wheel-type locomotive mechanisms equipped with passive linkages have successfully verified their mobile performances in real applications, for example, Mars Exploration Rovers (MERs) like Sojourner, Rocky7, Spirit and Opportunity, ORF-L, CEDRA, SHRIMP, etc. Among those passive linkages, the rocker-bogie is well known, which consists of two structural elements called as “rocker” and “bogie”. A schematic diagram of a six-wheeled rocker-bogie mechanism and the real photograph of Spirit adopting this mechanism are shown in Fig. 1.1 and Fig 1.2, respectively. The two-wheeled bogie is connected to the rocker through a pivot and two rockers on both sides are coupled to each other via a differential joint. Since all wheels of the rocker-bogie mechanism can keep in contact with the ground under various environments, it is possible not only to equilibrate the pressure of each wheel on the ground but also to effectively move forward/backward. Also, this mechanism allows a mobile robot to maintain its balance at the average pitch angle of both rockers so that the possibility of tip-over can be reduced.

In order to improve the climbing capability of a wheel-type mobile robot especially against structured terrains such as steps and stairs, several mechanisms have been developed on the basis of the rocker-bogie

**Table 1.1: Description of rocker-bogie system**

<table>
<thead>
<tr>
<th>Developer</th>
<th>NASA Jet Propulsion Laboratory (JPL), California Institute of Technology (Caltech)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel formula</td>
<td>6x6x4</td>
</tr>
<tr>
<td>Number of actuators (mobility)</td>
<td>10</td>
</tr>
<tr>
<td>Wheel diameter</td>
<td>25 cm</td>
</tr>
</tbody>
</table>

**Fig 1.1 Conceptual design of rocker bogie mechanism**

**Fig 1.2 Mars rover design by NASA**

1.1 The Taguchi method

The Taguchi method is a systematic design approach to find an optimal value of each parameter by design of experiments or simulations. Compared to the theoretical optimization approaches which generally demand complicated mathematical expansions, it is quite simple and cost-effective not only in formulating the objective function but also in satisfying the multiple quality requirements simultaneously. In this
method, all primary factors that affect the performance measure such as signal-to-noise (S/N) ratio may be classified into two categories: control and noise factors. Since the control factors can be chosen by a designer, they are easily adjustable to have desired values but the noise factors are difficult to control so that they may cause variations or detrimental effects to the product quality. Therefore, such parameters as shown in Fig 1.3 the wheel radii (R1, R2 and R3) and the link lengths (L1, L2, L3 and L4) are selected as control factors and three stairs in Fig.1.2 are selected as noise factors, respectively.

1.2. Optimization process with the Taguchi method

This chapter introduces the optimization process with the Taguchi method. To optimize the stair climbing ability of rocker-bogie mechanism, two cases of stair-climbing situations are suggested. Therefore the optimization objective function is defined separately for each case, and the Taguchi method is applied for the optimization sequence.

1.2.1 Application of the Taguchi Method

The Taguchi method was originally developed for quality engineering and for evaluation and improvement of a product’s robustness, tolerance specifications, and quality management of a production process. It does not draw upon complicated probability or statistical analysis. This methodology also can be applied to kinematic parameter optimization, which this paper presented. With this method, an optimized solution can be obtained by design of experiments, which normally demands complicated mathematical expansion in the theoretical approach.

The Taguchi method divides the independent variables into controllable factors and noise factors. Controllable factors can be maintained to a desired value, while noise factors may not be controlled. The Taguchi method can realize a robust design, which can maintain high performance as well as insensitivity to noise factors. In this section, the Taguchi method is applied in designing the simulations for maximizing the ability of stair-climbing.

1.2.2 Problem statement

To guarantee excellent performance in climbing up various stairs, an optimization for kinematic design parameters of mechanism is carried out. The link parameters and three wheel radii of rocker bogie mechanism (L1, L2 L3, L4, R1, R2 and R3) as shown in Fig are to be optimized using Taguchi method and these optimized parameters will be used in design, simulations and manufacturing. Mathematical modeling would be done in ANSYS rigid body Dynamics. To improve the reliability of this research through production the experimental prototype will be built. This robot platform will be used as a base robot platform as work of detection of explosives at public places, prevention of fire and detection of radioactivity leak.

![Fig 1.2 Different types of stair sizes](image)

1.2.3. Noise Factor

In this optimization problem statement, three shapes of stairs to be climbed by rocker-bogie mechanism are chosen as noise factor. Fig. 1.2 shows the scheme of stairs sizes.

1.2.4 Kinematic Model

As the performance measure to evaluate the quality of chosen link parameters in the presence of noise factors, the S/N ratio is introduced in the Taguchi method. The principal goal of the optimization is to maximize the S/N ratio because the S/N ratio becomes higher, the effect of random noise factors on the performance can be reduced. It is worthwhile to note
that the objective of this optimization is to minimize the area between the trajectory of CM and the straight line determined by each stair so that this optimization corresponds to the smaller-the-better case. Therefore, among various types of S/N ratios, the following one is selected considering the objective of this optimization.

\[
S/N = -10 \log_{10} \left( \frac{1}{N} \sum_{i=1}^{N} y_i^2 \right) \quad \text{(dB)}
\]  

(1)

Where N is the number of repetitions in simulations and yi is the performance value of the ith simulation. In this study, since the optimization is carried out with respect to three types of stairs in Fig 1.2, N is equal to the number of stairs and yi denotes the area between the trajectory of CM and the straight line determined by the ith stair. It is noted that to maximize S/N ratio in Eq. (1) is equivalent not only to minimize each area yi, i=1, 2, 3, but also to minimize the variation between them since the selected S/N ratio in this study can be rephrased as follows:

\[
S/N = -10 \log_{10} \left( \frac{y_1^2 + y_2^2 + y_3^2}{3} \right)
\]

\[
= -10 \log_{10} \left( \frac{y_1 + y_2 + y_3}{3} \right)^2 + \frac{(y_1-y_2)^2 + (y_2-y_3)^2 + (y_3-y_1)^2}{3} \]

Fig.1.4 Illustration of objective function

In order to improve the climbing capability of a wheell type mobile robot especially against structured terrains such as steps and stairs, several mechanisms have been developed on the basis of the rocker-bogie so that a few mobile robots can climb even steps of twice their wheel diameter. However, they often suffer from undesired phenomenon that some wheels float from the ground while climbing steps and stairs, which may cause instability of the mobile robot. It is worthwhile to note that a trajectory of centre of mass (CM) may serve as a tool for effectively predicting such undesirable phenomenon which is likely to occur at the moment the trajectory of CM drastically or discontinuously changes. Therefore, it is highly required to make the trajectory of CM as smooth as possible, which implies that the trajectory of CM must be close to a straight line whose slope is determined by a step or a stair. Since this requirement on the trajectory of CM minimizes the required motor power, the possibility is increased that the mobile robot can efficiently climb a step or a stair even for the relatively low friction coefficient.

2. Multi Body Dynamics (MBD)

Mechanical systems often contain complex assemblies of interconnected parts undergoing large overall motion. Examples can be found in a wide range of applications including suspension assemblies in ground vehicles, robotic manipulators in manufacturing processes and landing gear systems in aircraft. Simulating the motion of these systems by assuming fully flexible parts and then deploying traditional finite elements methods for the solution is computationally expensive, often making design exploration and optimization impractical. For a faster, more efficient solution to this class of problems, ANSYS provides an add-on module for rigid multibody dynamics analysis. With a minimal investment in model setup and computational resources, ANSYS Rigid Dynamics leads to a deep understanding of the motion and stability of mechanical systems earlier in the development cycle, when informed engineering decisions are critical. Then, if more fidelity is required as detailed designs emerge, an ANSYS Rigid Dynamics model can easily be converted to a partially or fully flexible representation, one that is capable of capturing large deformations and material nonlinearities.

3. Kinematic Model

Kinematical model of required mechanism is built which is shown in Fig.3.1
Fig. 3.1 Kinematic Model

Fig. 3.2 Simulation environment

4. Simulation Results

Various results of simulations are as follow

Fig. 4.1 x displacement of joint general- stair to wheel 1

Fig. 4.2 displacement of joint general- stair to wheel 1
Fig. 4.4 displacement of center of mass x, y, and z direction

Fig. 4.5 Graph of Joint Velocity VS time

Fig. 4.6 shows energy summery of the robot while climbing the stairs. The green colour line shows the variation of total external energy of the robot with respect to time. The red colour line indicates the variation of total energy of robot with respective time. The blue colour line indicates the variation of potential energy of robot with respective time.

Fig. 4.6 Energy Summery for stair climbing (300 X 100)

Fig. 4.7 Total force required during stair climbing (300 X100) on joint

Fig. 4.8 Maximum normal force required during stair climbing

5. Conclusion

The link parameters of the rocker-bogie mechanism are to be optimized via the well-known Taguchi method to improve its climbing capability as well as adaptability for various types of the stairs. In order to guarantee the stable behaviour of the proposed rocker-bogie mechanism during climbing the stair, the area between the trajectory of its CM and the straight line whose slope is to be determined by the stair is minimized by the Taguchi method under kinematic constraints to prevent the interferences between the mobile robot and the ground. As a result, the CM trajectory of the optimized rocker-bogie mechanism becomes close to the straight line compared to general
rocker-bogie mechanism and Mars rover Spirit and also, the shortcoming of the general rocker-bogie mechanism such as undesired backward movement is considerably reduced, which implies that the proposed rocker-bogie mechanism enables climbing of the stair more rapidly and efficiently. As a criterion to evaluate the climbing performance of the proposed rocker-bogie mechanism, the friction requirement metric is chosen. A suitable locomotive strategy such as the motor torques to prevent slip is derived based on the kinetic analysis to reflect the states of the proposed rocker-bogie mechanism interacting with the ground. Through extensive simulations in Rigid body dynamics, it is verified that the suggested locomotive strategy from the kinetic analysis makes the proposed rocker-bogie mechanism less susceptible to slip so that it can climb the step more efficiently.

5. References


3. Alok Kumar Pandey and Dr R. P. Sharma “Simulation of eight wheel rocker bogie suspension system using MATLAB ” published by IJMET March 2013.


