Design and Kinematics Modeling of a 1-DOF Compliant Mechanism

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Abstract
This paper presents the development of a compliant mechanism that works from displacements using a flexible material. This gripper has 1-Degree Of Freedom, with the purpose of being used in Medical applications such as cutting ducts and nerves of the human body. The design is validated using the software CAD SolidWorks, a finite element analysis was executed.

Keywords
Compliant— Mechanism—Gripper— Freudenstein

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Contents

Introduction

The purpose of this paper is to present a compliant mechanism (Gripper) that can be fabricated in a single plane, making it ideal for micro fabrication and macro-scale manufacturing processes.
Fully compliant mechanisms derive all of their motion from the deflection of flexible members, and are often used in place of mechanisms that would otherwise consist of linkages and springs [Howell, 2001].

They are frequently used in precision machinery and positioning because the elimination of joint pairs also eliminates the effects of joint clearances, wear, and friction.
[Hubbard et al., 2004].

This gripper is a set of compliant mechanisms based on a rigid-body model. The design of the mechanism is discussed in the following section. The model is then verified with finite element analysis (FEA).
As part of this work, a program that calculates the forces, displacements and stresses of a frame was made by using Matlab Software.

1. Methods

The gripper is designed by applying traditional kinematic synthesis techniques and then using a rigid-body model to create an equivalent compliant mechanism.

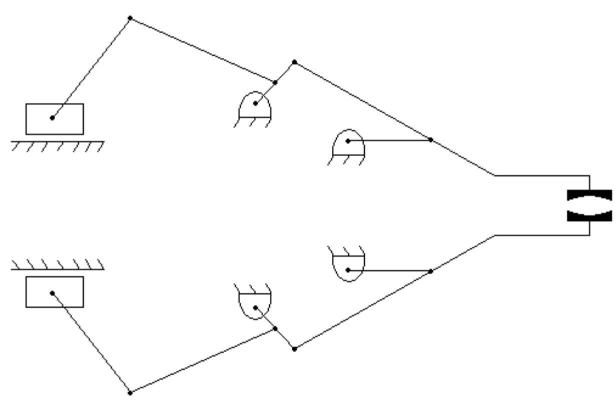

Figure 1. Rigid-body Model

1.1 Four Bar Linkage

Using the equation of Freudenstein the lengths of the bars were calculated. First of all the four bar mechanism shown in the figure below was calculated.

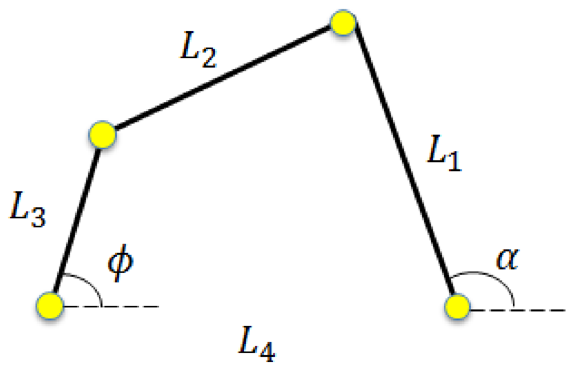

Figure 2. 4 bar mechanism

$$R_1 \cos\alpha - R_2 \cos\phi + R_3 = \cos(\alpha - \phi) \tag{1}$$

Where

$$R_1 = \frac{L_4}{L_3},\ R_2 = \frac{L_4}{L_1},\ R_3 = \frac{L_4^2 + L_3^2 + L_1^2}{2L_1L_3} \tag{2}$$

In order to solve the lengths of the bars, it is necessary to create a function described by three relations.

$$\phi_1 \rightarrow \alpha_1$$
$$\phi_2 \rightarrow \alpha_2$$
$$\phi_3 \rightarrow \alpha_3$$

Replacing the values of the angles, the following equations are obtained.

$$R_1 \cos\alpha_1 - R_2 \cos\phi_1 + R_3 = \cos(\alpha_1 - \phi_1) \tag{3}$$

$$R_1 \cos\alpha_2 - R_2 \cos\phi_2 + R_3 = \cos(\alpha_2 - \phi_2) \tag{4}$$

$$R_1 \cos\alpha_3 - R_2 \cos\phi_3 + R_3 = \cos(\alpha_3 - \phi_3) \tag{5}$$

$$\phi_1 = 72^\circ \quad \alpha_1 = 106^\circ$$
$$\phi_2 = 75^\circ \quad \alpha_2 = 110^\circ$$
$$\phi_3 = 90^\circ \quad \alpha_3 = 180^\circ$$

The following lengths result from solving the equations (3),(4) and (5), and assuming $L_4 = 80mm$.

$$L_1 = 26.48mm$$
$$L_2 = 62.81mm$$
$$L_3 = 32.88mm$$

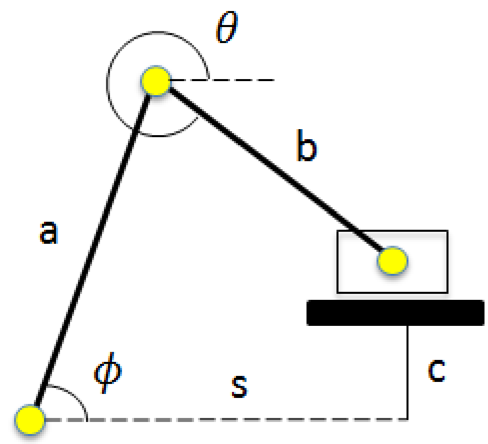

Figure 3. Slider mechanism

1.2 Slider Mechanism

In this section the lengths of the bars of the slider mechanism (Figure 3) are found by using the Freudenstein's formulation.

$$R_1 s \cos\phi + R_2 \sin\phi - R_3 = s^2 \tag{6}$$

Where

$$R_1 = 2a, \quad R_2 = 2ac, \quad R_3 = c^2 + a^2 - b^2 \tag{7}$$

In order to solve the lengths of the bars, it is necessary to create a function described by three relations.

$$\phi_1 \rightarrow s_1$$
$$\phi_2 \rightarrow s_2$$
$$\phi_3 \rightarrow s_3$$

$$R_1 s_1 \cos\phi_1 + R_2 \sin\phi_1 - R_3 = s_1^2 \tag{8}$$

$$R_1 s_2 \cos\phi_2 + R_2 \sin\phi_2 - R_3 = s_2^2 \tag{9}$$

$$R_1 s_3 \cos\phi_2 + R_2 \sin\phi_3 - R_3 = s_3^2 \tag{10}$$

$$\phi_1 = 160^\circ \quad s1 = 8$$
$$\phi_2 = 155^\circ \quad s2 = 9$$
$$\phi_3 = 150^\circ \quad s3 = 10$$

solving the equations (8), (9) and (10), the following dimensions are obtained:

a = 12.2 mm
b = 202.1 mm
c = 16.6 mm

1.3 Compliant Mechanism

After the mechanism was designed with rigid-body kinematics, the rigid-body model was used to convert it to a compliant mechanism. This is referred to as rigid body replacement synthesis[Masters and Howell, 2002].

First, it must be decided whether the pin joints will be replaced by small-length flexural pivots or whether some of the rigid links will be replaced with flexible segments.

For the calculations of the flexural pivots lengths, the following equations were used

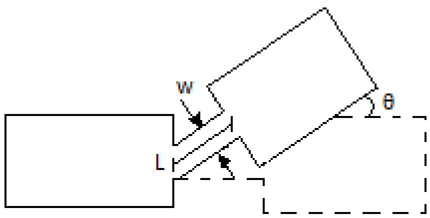

Figure 4. Length of the flexural pivots

$$L = \frac{w\theta E}{2\sigma_y} \tag{11}$$

$$\theta_1 = 15^\circ \quad \theta_4 = 24^\circ$$
$$\theta_2 = 6^\circ \quad \theta_5 = 2^\circ$$
$$\theta_3 = 30^\circ \quad \theta_6 = 44^\circ$$
$$\theta_7 = 42^\circ$$

The material chosen for the compliant mechanism was high density polyethylene, with the following properties :

E = 107 MPa
$\sigma_y = 22MPa$
w = 2mm

After applying the equations, the following lengths are obtained.

$L_1 = 10.66mm$
$L_2 = 4.260mm$
$L_3 = 21.32mm$
$L_4 = 17.06mm$
$L_5 = 1.420mm$
$L_6 = 31.28mm$
$L_7 = 29.85mm$

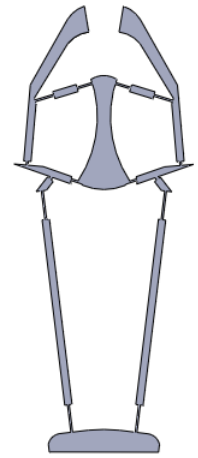

Figure 5. Compliant Mechanism

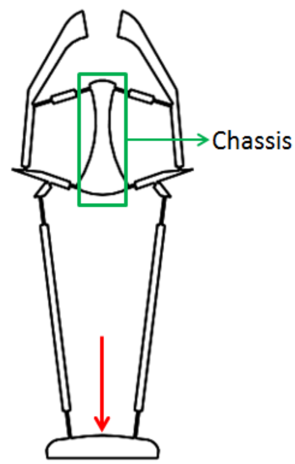

Figure 6. Boundary Conditions

2. Results and Discussion

Now, the results of finite element analysis will be treated in this part showing the necessary force for three different displacements, applying the boundary conditions.

2.1 Non-Linear Analysis

A non-linear analysis applying different displacements was done in the bottom section of the Compliant mechanism.

The figures shown illustrate the three different results, taking into consideration the boundary conditions.

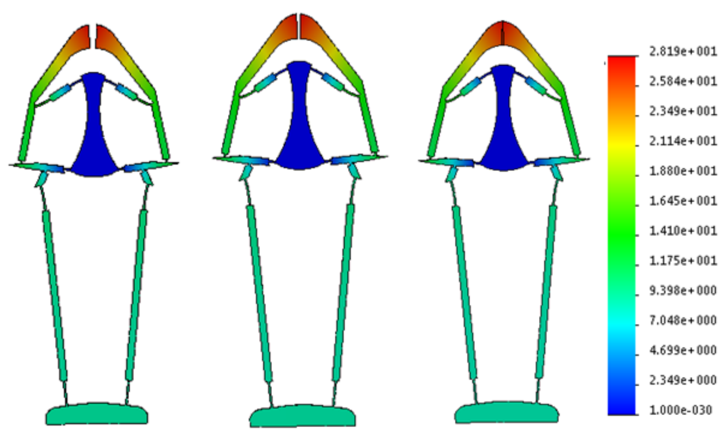

Figure 7. Displacements

Table 1. Table of Results

Results	
Displacement	Force
8 mm	2.34
9 mm	2.73
10 mm	2.827

2.2 Natural Frequency Analysis

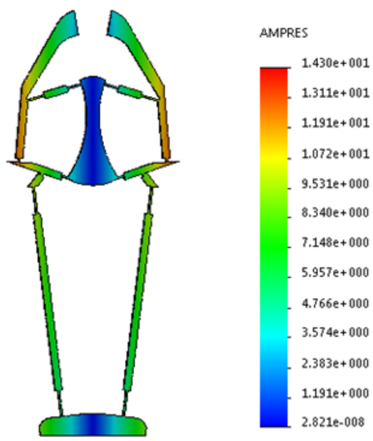

Figure 8. Natural Frequency

By using the CAD SolidWorks, the natural frequency of the gripper was analysed in order to find the natural movements. In the analysis, the open-close movement appeared in the third amplitude.

2.3 Frame

This subsection pretends to show the gripper in a frame form, it was used to analyse the forces, displacements and stresses of the frame using the code programmed in Matlab. The code is at the end of the paper, with the corresponding manual.

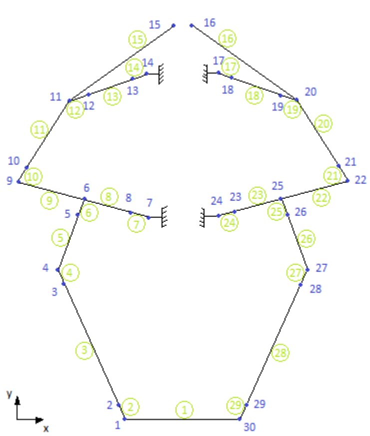

Figure 9. Frame

3. Applications

The compliant mechanism design in this paper has potential use in micro-scale devices. Some possible applications are end effectors and actuators that can cut duct and nerves of the human body. It can also be an instrument in surgeries making the manufacturing and small pieces assemblies easier.

4. Conclusions

Using the Freudenstein equations the authors guaranteed the efficiency of the mechanism and the dimensions needed for the intended purpose. The cost of the manufacturing of a compliant mechanism is lower and also takes less time. It can be done with a single machine and no assemblies are needed. This allows the manufacturing process to be easier. As the manufacture is easier, when the mechanism fails there is no need to replace some parts, a new mechanism will take its place.

5. Acknowledgments

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