Optimal Design of a Novel Micro-Gripper with Completely Parallel Movement of Gripping Arms

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Abstract—This paper presents the optimal design and analysis of a microgripper which has absolutely parallel movement of the gripping arms when it grasps or releases micro objects. By employing a compact displacement amplifier and several flexure supporting hinges, a novel gripper with simple symmetric structure driven by piezoelectric actuators has been designed. The kinematics and dynamic modeling of the gripper are conducted by resorting to compliance and stiffness analysis based on matrix method. The safety factor of the gripper is analyzed and conducted. Radius basis functional network (RBFN) is used to solve the analytical equations. At last, the parameters are optimized via RBFN based multi-objective GA optimization method, a set of optimal solutions can provide with good suggestions for parameters selections.

I. INTRODUCTION

Nowadays, the increased demands of the technical applications in micro/nano field lead to increasing complexity of the micro devices. These devices can only be assembled by all kinds of micro/nano-position and gripping devices. It is essential to develop a set of new assembling technology which can be used to handle very small parts. The problems of handling very small micro-optical, micro-electronic and micro-mechanical elements in micro/nano-meter range can be solved by using micro/nano-position stages [1]. In view of the increasing functionalities of such systems, special micro-gripper is also a very active research field. A great number of novel microgrippers proposed for the micro/nano application can be found in literature [2]. There are several typical micro-grippers who are different in using new materials, adopting new actuators, and owning diversified mechanical structures. A typical class of electrostatic microgrippers is featured with silicon and silicon-processed technology. Electro-thermal actuator can also be used in developing a typical microgripper. Shape memory alloy (SMA) allows high accuracy in micro-positioning and has great advantages such as large deformation, strong recovery force and a high work density. Moreover, Electro active polymers are utilized as actuators in micro grippers. The three-gripper fingers based on electro active polymers are developed, which are difficult to fabricate by resorting to silicon processing method. Also, there are a lot of literature focused on piezoelectric actuator and flexure hinges. However, most already developed microgrippers can only realize with two opposite rotational movement of the gripping arms to grab a part just like forceps. On one hand, in case of micro parts with curved or especially a sphere surface such as micro lenses, the holding force will make the gripped object have the trend of moving to the longitudinal axes of the microgripper and push it out of the gripping arms. It is hard for the gripper to hold and transfer it tightly as shown in Fig.1. On the other hand, the arms always have a tiny movement along with the longitudinal axes of the micro-gripper, although it can be made of the micro-positioning stage, it really brings some troubles to the positioning system. This negative effect can be avoided if the gripping process is realized without any rotational like movement just as shown in Fig.2. This can be achieved by using a gripping mechanism with parallel movement of both gripping arms. In this case a reliable gripping process can be guaranteed. Aiming for solving these problems, a novel microgripper with completely parallel movement of gripping arms is designed and optimized in this paper.

As one of the most important issues, the optimal design of the mechanical system is necessary before it is fabricated. However, the traditional optimization methods can only handle a few geometric variables due to lake of convergence. Genetic algorithms have applied the powerful...
and broadly applicable stochastic search methods and optimization techniques, and they can escape from local optima. Besides, artificial neural networks (ANNs) have the capability of complex function approximation and generalization by simulating the basic function of the human nervous system in an attempt to partially capture some of its computational strengths. The integration of GAs and ANNs are suitable as one of the best candidates for addressing the performance optimization issue of the microgripper.

In the remainder of the paper, the design of the parallel-movement micro-gripper based on flexure hinges is presented in Section II, where one plenary micro-gripper featured with right circle hinges is proposed as an example for the subsequent studies. By resorting to the matrix method used in Section III, compliance and stiffness modeling of the gripper are performed in Section IV, and safety factor of the gripper are analyzed and conducted in Section V. In Section VI, the the parameters are optimized via RBFN based multi-objective GA optimization method, a set of optimal solutions can provide with good suggestions for selecting parameters. Finally, some concluding remarks are summarized in Section VI.

II. DESIGN OF THE MICROGRIPPER

In a rigid-body mechanism, a gripper with two fingers can be designed like a pair of pliers. With a screw actuator and some rotational hinges, we can figure out a parallel movement gripper with some parallelograms. Under the rules of parallelogram, the fingers of those grippers will move parallel towards each other but there is still a flaw of the fingers since they will move along the longitudinal axial direction. In micro-system field, most mechanisms are made based on compliant parts. So, it is a little bit difficult to realize all kinds of movement as easily as in rigid-body mechanism. Even so, those grippers proposed in the literatures do make great contributions in the field of micro-assembly or bio-electro-mechanisms systems. But when the curved micro parts in terms of sphere lens or micro-particles are handled, it is necessary to develop a new gripper which can solve above problems. Inspired by the amplifier mentioned in the totally decoupled flexure-based XYZ parallel micromanipulator stage [3], we think why not use the translational movement of the amplifier to construct a parallel movement gripper. After carefully surveying related research work, we found that there are very few precise microgrippers who can move their arms or fingers in a large range, most of their moving displacements are within 100μm, very few can reach 300μm. Then a new gripper is designed with several primary ideas as shown in Fig.3. Since it is difficult to mount it onto a micropositioner separately. Note that any other types of flexure hinges (e.g. elliptical, right angle, and corner-filleted hinges) can be adopted in the compliant microgripper design. As an example, the modeling and evaluation of the microgripper with half circle hinges and with two arms will be conducted in the following sections.

III. COMPLIANCE MODELING OF FLEXURE MECHANISMS BASED ON MATRIX METHOD

Various methods can be adopted in modeling the compliant mechanisms [4]. One of those typically method is pseudo-rigid body (PRB) which is based upon simplification analysis, only deformation around one axial is considered but other members of the mechanism besides hinges are assumed as rigid body and their deformations are neglected.

Here, it is assumed that the linear relation is established between force and deformation. Eq.1 shows the displacement of the tip of general beam when external forces are exerted on it. $f_n$ and $δ_n$ are the force and translational displacement in n-axis, respectively and $M_n$ and $θ_n$ are the moment and rotational displacement around n-axis, respectively.

$$[δ_x, δ_y, δ_z, θ_x, θ_y, θ_z]^T = C_b[f_x, f_y, f_z, M_x, M_y, M_z]^T \quad (1)$$

And the $C_b$ is frequently used in flexure mechanisms which have been derived in several references, and the equation with best accuracy adopted in our calculation is reviewed in[4]. Additionally, referring to Fig.5., the local compliance
of the hinge is defined as \( C^0_i = C_h \), where the upper-right superscript describes the coordinate with respect to which the compliance is described throughout this paper, and "0" indicates the ground that will be omitted for the clarity of representation. The compliance \( C_i \) can be transferred onto another frame \( O_j \) by

\[
C^j_i = T^j_i C_i (T^j_i)^T
\]

(2)

where the transformation matrix takes on the following form:

\[
T^j_i = \begin{bmatrix}
R^j_i & S(r^j_i)R^j_i \\
0 & R^j_i
\end{bmatrix}
\]

(3)

Where \( R^j_i \) is the rotation matrix of coordinate \( O_j \) with respect to \( O_i \), \( r^j_i \) is the position vector of point \( O_i \) expressed in reference frame \( O_j \), and \( S(r) \) represents the skew-symmetric operator for a vector \( r = [x, y, z]^T \).

Generally, a flexure mechanism consists of \( n \) individual flexure elements connected in serial or parallel manners. In order to obtain the compliance model of the entire mechanism, the local compliances need to be transformed to a global frame chosen to describe the mechanism. Then, compliances connected in serial and stiffness connected in parallel can be, respectively, added together to generate the entire model of the flexure mechanism.

IV. COMPLIANCE MODELING OF THE MICRO GRIPPER AND ITS AMPLIFIER RATIO

We can observe that the gripper has a symmetric structure as shown in Fig.7(a), and the input forces are exerted on both points of A and B with the same amount, so we can analyze the relationship between the input forces and the input and output displacements step by step as follows.

1) Input Compliance Modeling: The output compliance \( C_A^1 \) is defined as the compliance of input end point \( A \) with respect to the ground \( O_1 \). As all the limbs and hinges connected serially or parallel, as shown in Fig.7(a). It can be observed that the compliance \( C_A^1 \) can be described as two parallel limbs(\( C_{L12} = C_{L1}/C_{L2} \)) connected parallel with other two serially limb groups(\( C_{L34} = C_{L3}/C_{L4} \) and(\( C_{L5678} = (C_{L5}+C_{L7})/(C_{L6}+C_{L8}) \)), in each limb group, there are two limbs connected in parallel. The compliance of input end point \( A \) with respect to the ground \( O_1 \) can be derived as

\[
C_A^1 = [(C_{L12})^{-1} + (C_{L34} + C_{L5678})^{-1}]^{-1}
\]

(4)

where

\[
C_{L12} = [(C_{L1}^{-1} + (C_{L2}^{-1})^{-1}]
\]

\[
C_{L34} = [(C_{L3}^{-1} + (C_{L4}^{-1})^{-1}]
\]

\[
C_{L5678} = [(C_{L5} + C_{L7})^{-1} + (C_{L6} + C_{L8})^{-1}]
\]

Due to the property of symmetric structure, one quarter of the amplifier is picked out, as shown in Fig.6., for the purpose of calculating those compliances of each limb. The compliance \( C_{L1}^1 \) is defined as the compliance of the limb from \( O_2 \rightarrow O_3 \rightarrow O_4 \rightarrow O_5 \rightarrow A \) with respect to \( O_1 \), which can be derived by

\[
C_{L1}^1 = T_4^1 C_4 (T_4^1)^T + T_2^1 C_2 (T_2^1)^T
\]

(5)

The compliance \( C_{L5}^1 \) is defined as the compliance of the limb from \( O_3 \rightarrow O_4 \rightarrow O_6 \rightarrow A \), as shown in Fig.6., which can be derived by

\[
C_{L5}^1 = T_4^1 C_3 (T_4^1)^T + T_7^1 C_7 (T_7^1)^T
\]

(6)

Due to the property of symmetric structure, the other compliances of the limbs can be derived easily by

\[
C_{L2}^1 = \overline{R}_x(\pi) C_{L1}^1 \overline{R}_x(\pi)^T
\]

(7)

where \( \overline{R}_x(\pi) = \begin{bmatrix} R_x(\pi) & 0 \\ 0 & R_x(\pi) \end{bmatrix} \). With the similar way, we can obtain the following compliance matrices \( C_{L3}, C_{L4}, C_{L5}, C_{L6}, C_{L7}, C_{L8} \).

2) The Displacement Amplification Ratio: As shown in Fig.7, it is assumed that only single side input force \( F_A \) is exerted on the point \( A \), it will produce two displacements as \( u_A \) and \( u_B \) at point A and B respectively.

\[
u_A = C_A^1 (1,1) F_A
\]

\[
u_B = u_A C_{L34}(1,1) C_{L5678}(1,1)
\]

(8)

During the gripping process, both point A and B will be exerted on the same amount of forces from the two ends of the PZTs, so we can get the input displacement for one side generated by the force of PZT as follows:

\[
u_{in} = u_A - u_B
\]

(9)

Therefore, the input compliance is

\[
c_{in} = u_{in}/F_A = C_A^1 (1,1) C_{L34}(1,1) C_{L5678}(1,1)
\]

(10)

We have obtained the relationship between the input forces, where PZT is exerted on point A and point B while the displacement is produced on point A and point
3

The gripper with only point A actuated

\[ \sigma_a = \sigma_a^l + \sigma_s \]

Firstly, if a notch hinge bears a bending moment around its rotation axis, the maximum angular displacement \( \theta_{max} \) arises when the maximum stress \( \sigma_{max} \) which occurs at the outermost surface of the thinnest portion of the hinge, reaches to the allowable stress \( \sigma_a \). Referring to [3], the relationship between the maximum stress and maximum rotation of the flexure hinge can be calculated by

\[ \sigma_{max}^r = \frac{E(1 + \beta)^{9/20}}{\beta^2 f(\beta)} \theta_{max} \]

where \( \beta = t/2r \) is a dimensionless geometry factor with the most accuracy range of \( 0 < \beta < 0.3 \) and \( f(\beta) \) is a dimensionless compliance factor defined in [3] as

\[
\begin{align*}
  f(\beta) &= \frac{1}{2\beta + \beta^2} \left[ 3 + 4\beta + 2\beta^2 \right] \\
  &+ \frac{6(1 + \beta)}{(2 + \beta)^{3/2}} \tan^{-1} \left( \frac{2 + \beta}{\beta} \right)^{1/2}
\end{align*}
\]

Secondly, the maximum tensile stress subject to the axial load may occur on the thinnest portions of flexure hinges constructing the displacement amplifiers or other links of the stage, which can be determined by

\[ \sigma_1^t = \frac{F_{in}}{S_{min}} = \frac{K_{in}Q}{wt} \]

where \( S_{min} \) denotes the minimum cross-sectional area of the hinge. Then, the safety factor can be seen as the function of \( t, R \), input compliance \( C_A \) and input displacement \( Q \) gives the relationship between the stiffness/compliance values and the architecture parameters of the gripper.

VI. PERFORMANCE INDICES OPTIMIZATION

The goal of structure parameters design, which is also called dimensional synthesis, is to confirm the best geometric configuration according to objective function and geometric restriction. To make sure the parallel movement gripper will possess well performance such as high system stiffness, wide operation range and large safety factor, dimensional synthesis for optimization is one of the most important steps in the design process of parallel movement gripper. Just as shown in Fig.9 and Fig.10, if the compliance is increased, the parameters of the right circular hinges’ \( r \) should be decreased and \( t \) should be increased. It is obvious that the safety factor is expected to be larger, so just in the inverse direction to vary the parameters \( r \) and \( t \). Fig.9 and Fig.10 are just used to show how the performance indices conflict with each other as there are only two parameters included in the variety. But in reality, the variety of any parameters will affect the performance such as compliance, safety factor and
Fig. 9. Stiffness of the gripper with respect to the parameters r and t

Fig. 10. Safety factor of the gripper with respect to the parameters r and t

Fig. 11. Test of the RBFN fitting performance

Fig. 12. Pareto-optimal solutions and Pareto frontier in solution space

amplification ratio, etc. So the optimization result will be a set for all kinds of different purposes of optimization.

The RBFN based GA is used as follows, three single objectives are combined with pareto optimal solutions to accomplish multi-objective optimization. Finally, the structure parameters of the flexure joints are optimized simultaneously, an optimal solution set is obtained.

A. RBF network

An ANN using radial basis function as activation function instead of sigmoid functions is called RBF network. The RBF is a function which puts the maximum value at its center point and decreases its output as the input leaves from the center. Typically the Gaussian function is used for the activation function. RBF Network is widely used in function approximation, time series prediction, control, and the network architecture is constructed with three layers: input layer, hidden layer and output layer. The input layer is made up of source nodes that connect the network to its environment. The second layer, the only hidden layer of the network applies a non-linear transformation from the input space to a hidden space. The nodes in the hidden layer are associated with centers that the hidden unit is activated through RBF using Gaussian function or other functions. The output layer neuron calculates the linear sum of values of the hidden neuron and outputs it. Here the Gaussian function is used as a basis function. Let $\Phi_j(x)$ be the $j$–th basis function, it can be represented as:

$$\Phi_j(X) = exp\left(-\frac{(X - C_j)^2}{2\sigma^2_j}\right) \quad (19)$$

Here, $X = (x_1, x_2, ..., x_d)^T$ is the input vector, $C_j = (c_{1j}, c_{2j}, ..., c_{dj})^T$ and $\sigma^2_j$ are the $j$–th center vector and the width parameter, respectively. The output of RBF network $y$, which is the linear sum of basis function, can be obtained by

$$y = \sum_{j=1}^{m} w_j \Phi_j(x) \quad (20)$$

where, $y$ is the output of the RBF Network, $m$ is the number of the hidden layer neuron and $w_j$ is the weight from $j$–th neuron to the output layer. A multi-input and multi-output RBFN can be constructed and trained via MATLAB ANN toolbox conveniently. As shown in Fig.[11], the output of the RBFN is tested and compared with the input surface. Since the two surfaces are matched well and it is hard to tell the difference, a slice is used to show the tiny difference between the fitting surface and the analytical equation created surface.

B. RBFN based GA multi-objective optimization

There are two general approaches to multiple-objective optimization. One is to combine the individual objective functions into a single composite function or move all but one objective to the constrain set. In the former case, determination of a single objective is possible with methods such as utility theory, weighted sum method, etc., in practice, it is very difficult to precisely and accurately select these weights because small perturbations in the weights can sometimes lead to quite different solutions. In the later case, the problem is that to move objectives to the constrain set, a constraining value must be established for each of these former objectives. This can be rather arbitrary. The second general approach is to determine an entire Pareto optimal solution set or a representative subset. A Pareto optimal solution set is a set of solutions that are non-dominated each other. While moving from one Pareto solution to another, there is always a certain amount of gains in the others. Pareto optimal solution sets are often preferred to single solutions because they can
be practical when real-life problems are considered since the final solution of the decision-maker is always a trade-off. Being a population-based approach, GA is well studied to solve multi-objective optimization problems because a generic single-objective GA can be modified to find a set of multiple non-dominated solutions in a single run. There are a lot of survey papers reported that the majority of approaches to multi-objective optimization were based on evolutionary approaches [5][6].

Although GAs or other methods can be adopted without ANNs to search the best solution set of variables. The main problem is that it is time-consuming especially when the parameters are diversified and the objective function is too complex that GAs cannot work well based on the analytical expression of the performance indices, especially for the case of multi-objective optimization. The error of the output of ANNs to search the best solution set of variables. The main disadvantage of GAs will not affect the computing accuracy with CPU. Since the trained neural network is ready for the objective function, the genetic algorithm can be implemented to search for the best solutions [7].

With the selection of stiffness, safety-factor and amplifier-ratio as the objective functions, the optimization conditions are stated as follows.
1) Maximize: input stiffness($k_{in}$), output stiffness, safety-factor($\sigma$), and amplifier-ratio($A_r$).
2) Variables to be optimized: $r$, $t$, $l$, $l_1$, $l_2$, $l_3$, $l_4$, $l_5$, $l_6$, $l_7$, $l_8$.
3) Subject to:
   a) amplifier-ratio $A_r \geq 6$.
   b) input stiffness value $k_{in} \leq k_{PZT}$.
   c) safety-factor $\sigma \geq 2.5$.
   d) Parameter ranges: $2.5mm \leq r \leq 6mm$, $0.3mm \leq t \leq 2mm$, $25mm \leq l \leq 50mm$, $0.1mm \leq l_1 \leq 5mm$, $5mm \leq l_2 \leq 20mm$, $5mm \leq l_3 \leq 20mm$, $5mm \leq l_4 \leq 20mm$, $20mm \leq l_5 \leq 60mm$, $5mm \leq l_6 \leq 30mm$, $20mm \leq l_7 \leq 40mm$, $10mm \leq l_8 \leq 30mm$.

As far as the given material(AL7075-T651) with a special thickness ($w = 10mm$) is considered, eight parameters mentioned above need to be optimized since their parameters can be designed by considering the length and width of the PZT with the addition of a proper assembling space. The amplifier ratio of the stage is specified to guarantee a travel range no less than 180$\mu m$ for the mobile arms.

After the implementation of the GA multi-objective optimization, Fig.12 shows one of the Pareto optimal frontiers, according to its trend, the designers can determine the final solutions depending on their performances. From this figure, the trade-off between the objectives of system stiffness, safety-factor and amplifier-ratio is demonstrated in the distributing trend of these Pareto points for compromising selection. Furthermore, through the observation of the optimal processing, it can be found that the objective values are mainly influenced by five parameters as $r$, $t$, $l_1$ and $l_5$. There are six optimum design points whose corresponding objective values and design parameters are shown in Tab.1. It shows that a set of satisfied optimal solutions, which provide enough information about alternative solutions for the decision maker with great diversity, can be obtained with Pareto based genetic algorithms.

### VII. CONCLUSIONS
A flexure hinge based microgripper with completely parallel motion is designed in this paper. The mechanical amplification is employed to make the gripper have a large motion range. In consideration of the most important issue for the micro/nano gripper, the performance indices including the input stiffness, safety factor and amplifier ratio are analyzed. With traditional optimization methods, only a few geometric parameters could be dealt with due to the lack of convergence of the optimization algorithm for multi-objective functions, the combination of RBFNN and GA with Pareto method are applied to obtain a multi-objective function solution set. Different emphasized goal can be reached with different solutions by selecting the solution set. Through selecting proper amplification ratio and the stroke of the PZT, the displacement of the gripping arms can reach 300$\mu$m which can be widely used in many precise micro operational field. Our future research will focus on the precision analysis, fabrication of the prototype, the gripping force measurement of the gripping fingers by strain-gauges and the force control strategy design considering the feedback of the gripping force.

### REFERENCES