Optimization parameter for microgripper based on triple-stair compliant mechanism using GTs-TOPSIS

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Abstract
In manipulating the assembly of micro-components, the symmetrical microgripper mechanism often causes destruction, damaging those components during manipulation, due to the phenomenon of non-uniform clamping force output from the clamp. From this disadvantage, a new asymmetric microgripper structure is proposed with stable output clamping force. The asymmetric microgripper structure will have a smaller output displacement than that of the symmetric structure. Therefore, to increase the output displacement gain, a flexible hinge with a triple-stair half-bridge-style mechanism (TSBM) is adopted to design the amplifier of the asymmetrical microgripper. The finite element method is applied to analyze the displacement and stress. The optimization process is performed based on the geometric parametric properties of the structure. Using the technology for order preference by similarity to ideal solution (TOPSIS) based on the Grey relationship analysis (GRA), we obtained the maximum displacement output and minimum stress. Results show that the maximum output displacement is 5,818 mm, and stress after analysis is 2,432 MPa. The test is conducted to verify the optimal results and the effectiveness of the optimization method. Finally, experimental experiments were performed, with a 4.8% difference from the FEA results. The results from the experimental test verify that the microgripper’s maximum displacement amplification ratio is approximately 58.2 times.

Keywords Microgripper mechanism · Triple-stair half-bridge-type · Grey relational analysis · Entropy weight · TOPSIS method

Abbreviations

| Variable          | Definition                                      | Unit          |
|-------------------|-------------------------------------------------|---------------|
| Incline angle, α  | Angle between the center of two flexure hinges and the parallel line. |               |
| Length, l         | Length of the flexure hingemm                   |               |
| Thickness, t      | Thickness of the flexure hingemm                |               |
| S/N, \(x_i^*\)    | Signal-to-noise ratio, used to define the quality of the performance and the normalized S/N. |               |
| GRC, \(\xi_i\)    | Array of the relationship between the ideal and actual normalized experimental results. |               |

| GRG, \(\gamma_i\) | Average obtained by multiplying the GRC by the weight can be regarded as the score obtained by each plan; the higher the score, the more important the plan. |
|-------------------|---------------------------------------------------------------------------------------------------------|
| \(D_k\)           | Summation of each attribute’s value for all array.                                                        |
| \(e_k\)           | Entropy of the specific attribute.                                                                       |
| \(E\)             | Summation of \(e_k\).                                                                                     |
| \(\beta_k, w_k\)  | Relative weighting factor and normalized relative weighting factor.                                       |
| PIS, \(D^+\)      | Maximum benefit criteria with minimum cost criteria.                                                      |
| NIS, \(D^-\)      | Minimum benefit criteria with maximum cost criteria.                                                      |

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1 Introduction

In the microscopic world, when manipulating with micro-particles, the dexterity, accuracy, and speed of the manipulation will be improved when one can feel the interaction with the micro-part and controlled in real-time. The development of such a sensing micromanipulator system is of interest in many areas, e.g., cell surgery, laparoscopic surgery, microrobots, and micro-assembly [1–8]. The micro-grippers developed based on the flexing properties of parts to create the desired movements include high-precision motion, light, frictionless, and compactness, to name a few. These characteristics improved the effect of micro-manipulation operations which can be realized with many kinds of actuation such as piezoelectric actuator, electrostatic, electromagnetic microgrippers, shape-memory alloy (SMA), and electroactive polymers (EAPs) [9–15].

The piezoelectric actuator is normally used in micro-grippers such as the operator because of its high force, high accuracy, high-frequency operation, and small size [16–19]. Thus, it is widely applied in industrial fields such as robotics and micro-nano manufacturing. The microgripper design used in bonding IC and LED is controlled by a flexible PZT ceramic stack [19]; Zubir et al. [20] used PZT ceramics for designing a microgripper for micro-manipulation. Piezoelectric gripper is remarkable when applying in precision manipulating (Rakotondrabe and Ivan) [21]. The sliding-mode control methodology was applied for piezoelectric drive, which overcomes the problem of parameters including the effects of hysteresis and disturbance in piezoelectric drive systems without compensation (Liaw et al.) [19]. Multi-layer piezoelectric materials were proposed for a large displacement and high force to expand its applicability possibilities (Yang and Xu [22]; Wu and Xu [23]). Nachippavan et al. [9] application model of piezoelectric microgripper for unmanned aircraft was also considered, analysis of the arbitrary variable structure of microgripper was performed, and COMSOL MULTIPHYSICS 4.2 software was used for piezoelectric analysis. Research has shown that the material that creates piezoelectric microgripper also significantly affects the degree of movement of the mechanism, specifically compared to conventional materials such as silicon, polysilicon, and silicon dioxide. The result of silicon dioxide is better than the other materials. The total displacement of the mechanism after structural modification showed a significant increase compared to the existing microgripper. Tilok Kumar Das et al. [24] introduced double-bridge, triple-bridge, and multi-bridge mechanisms with the characteristics of amplification of displacement and linear output motion. The microgripper mechanism was proposed as a design based on the double-stair bridge-type mechanism with three levels of the displacement amplification mechanism used to expand the displacement of piezoelectric actuators, the ability to respond quickly to a frequency of 1044Hz.

The symmetric and asymmetric structural is applied to design the mechanism of microgrippers. With symmetrical construction, most clamping mechanisms use the form of symmetrical construction, which has an advantage in the application of double-displacement amplification, and they can adapt to enlarge range of work clamping and assembling (Bao, et al) [25]. A single-stage microgripper with a symmetric structure based on the principle of lever amplification [26] was designed to fulfill the biggest displacement amplification but unable to achieve parallel clamping motion. Cui et al. [27], based on the rule to lever to design a symmetrical microgripper that could be complete the parallel clamping motion. However, the maximum actual output force between the both sides of the function are different, so it will lead to the destroy of the micro-component during the gripper clamping. Sun et al. [28] and Wang et al. [29] by using the principle of lever amplification and triangular gain, they designed a multiple-stage symmetrical microgripper, which could achieve parallel clamping of the grippers and bigger displacement amplification. However, the microgripper designed by them was unable to obtain a stable clamping motion. From above the review, it indicated that the movement of both sides the microgripper cannot achieve synchronized, so errors in the production and installation process cannot be avoided. Asynchronous motion is a main limitation in symmetric structures. It affects the working quality as well as the precise position control. Thus, it requires motion binding to be able to control the movement of the two clamps simultaneously. To avoid the disadvantages of symmetric microgrippers, an asymmetrical structure is proposed to design with one side of the microgripper responsible for displacement, while another side is unmoved. So there will be no non-synchronization of the two gripper micros, and this is the most significant advantage of the types of asymmetric structure. On the other hand, there is also no asynchronous force during micro-component execution. Therefore, the micro-parts will not be destroyed by unilateral force because only one clamp-side of the microgripper can be moved. Koo et al. [30] also based on the principle of lever amplification designed an microgripper with an asymmetric structure to achieve a stable grasp of the grippers but unfortunately which could not grasp in parallel. Xing et al. [31] designed an asymmetric microgripper that could complete parallel grips of jaws. However, the structure has a small amplification. In addition, during the process fabrication of microgripper, the optimization of design parameters is necessary to get more efficient performance by eliminating unnecessary steps, saving time, reducing errors numbers, and avoiding duplication of work. For example, the finite element model was simulated for...
optimization microgripper structure with consideration of the properties of PSA, nonlinear geometry limit, and established static limit as well as dynamic bonding [32]. A hybrid Taguchi-teaching learning-based optimization algorithm (HTLBO) was utilized to optimize compliant microgrippers; the advantages of the hybrid approach are simplicity and fast computation, achieving desired optimal results [33]. Shunli Xiao et al. [34] optimize design parameters in the microsystem before fabrication is essential. The RBFN-based multi-objective GA optimization method was applied to optimize the design parameters of the microgripper. The calculation process of an algorithm will receive the best set of solution variables, finally providing the best-suggested results to choose the parameters microgripper. Genetic algorithms have also been applied to solve the parameter appreciation problem of MEMS technique based on microgripper [35]. The fuzzy-TOPSIS and Grey relationship analysis method was applied to select the optimal cutting parameter values [36]. Fuzzy-TOPSIS can apply for the pick of optimal process parameters in micro-manufacturing technology [37]. A new optimal selection method created by combining fuzzy set theory, the AHP, and TOPSIS was applied to the mining method selection which was then used to choose the most appropriate mining method for panel 43101 in the Liang-shuijing coal mine in China [38]. The best choice for various non-traditional machining processes using the integration of fuzzy with AHP and QFD methods has been successfully made [39]. A new method combining NN–GA has been proposed and is applied to model and optimize the process parameters such as pulse width, pulse frequency, cutting speed, and gas pressure of Ti-alloy plate cutting pulse laser [40]. Aside from this, multi-criteria decision-making (MCDM) is gaining popularity in renewable energy systems. The evaluation, selection, and ranking of renewable energy systems in Turkey will have many incompatible criteria causing difficulties in the research process. The proposed entropy weight and fuzzy-TOPSIS methods are applied to support quick and efficient process decision-making [41].

Based on the above references, both single-stair bridge-type and double-stair models were studied by other authors. To our best knowledge, previous studies have not discussed the structure of triple-stair; thus, this paper developed a novel microgripper mechanism for micro-manipulation and assembly. A new asymmetric microgripper mechanism based on the triple-stair half-bridge-style mechanism is investigated to induce a steady output force of the clamp. With a triple-stair structure, the stiffness of the model will be increased, and the new model will withstand a greater input force than a single and double-stair structure. Besides, it still ensures a large output amplifier displacement. This design accomplishes its grasping process on a two-stage amplification.

A detailed parametric study was conducted to analyze the influence of various geometrical parameters such as incline angle (α), thickness (t), and length (l) of the flexure hinge for the output displacement amplification ratio and the stress of the microgripper structure. Providing optimal design-selected variables to achieve maximum displacement with minimum stress multi-objective optimization is applied using a new integrate method by combining the GRA technique-based TOPSIS method and the entropy measurement method to optimize the output parameters of the asymmetric microgripper. The GTs-TOPSIS approach combines the priorities of both GRA and TOPSIS. The uncertainty handling capabilities of GRA combined with the more realistic model in TOPSIS allow for a balance between input parameters. This method has a simple calculation and is fast and effective. Finally, verification experiments were conducted to confirm the optimal results obtained.

Fig. 1 Model design. a Three-dimension model. b Two-dimension drawing

2 Structural design and methodology

2.1 Structural design of the model

The dimension of the specimen microgripper is 110mm × 78mm × 10mm. The 2D and 3D factors used to model the microgripper mechanism are shown in Figure 1. The asymmetric structure has been proposed to develop a piezoelectric actuator microgripper based on a compact flexure hinge. The microgripper construction uses a
corner-filleted flexure hinge, fixed jaw, moving function, and a piezoelectric actuator (PZT).

Additionally, a two-stage amplifier included a triple-bridge amplifier, and a single-lever amplifier was designed to improve the clamping stroke and obtain the highest output displacement. The triple-bridge-type amplifier and lever amplifier were directly connected in a series to obtain a bigger displacement amplification. The structure of the triple-stair was chosen to develop a compact flexure hinge-based piezoelectric actuator microgripper. With a triple-stair structure, the stiffness of the model will be increased, which can withstand greater input force and adopted at a higher frequency than a single- or double-stair structure. Besides, it still ensures a large output amplifier displacement.

2.2 Finite element method simulation

The characteristics of PLA are shown in Table 1. The density is 1.25 mg/m³. The model was designed by using Autodesk Inventor software and analyzed by FEA embedded in ANSYS.

The fixed support is used for three holes outside and two holes inside. The displacement input controlled by the piezoelectric actuator is shown in Figure 2.

Table 1 Mechanical properties of PLA

| Property          | Value     |
|-------------------|-----------|
| Tensile strength  | 55 MPa    |
| Young’s modulus   | 3.5 GPa   |
| Shear modulus     | 40 GPa    |

3 Optimal method

3.1 Decision of parameters

According to previous research, the thickness, length, and incline angle of flexure hinges have significantly affect the output displacement of the microgripper. Therefore, in this paper, three parameters, i.e., the thickness of the flexing hinge, length of the flexing hinge, and incline angle of the flexing hinge, are chosen to analyze the influence of design parameters of the mechanism triple-stair bridge-type mechanism to the output of the microgripper mechanism.

The output displacement is chosen as the objective function, and the output stress is controlled under the limitation of the material. The concentrated stresses at the corners of the FHs need to be released to avoid the shear stress. In this paper, the triple-stair bridge-type mechanism is used to develop a piezoelectric actuator microprocessor based on curvature; thus, the thesis focuses only on the analysis and optimization of geometrical parameters of flexure hinge at the triple-stair bridge-type area:

\[
\begin{align*}
    t & \in [0.3, 0.7], \\
    l & \in [3, 8], \\
    \alpha & \in [0.9, 1.5].
\end{align*}
\]

3.2 Effects of parameters

The effect of variable t is observed, while the value of l and the \( \alpha \) was fixed. The displacement output and stress output were analyzed to consider the best value of t.
The results are shown in Figure 3. When the thickness increases from 0.3 to 0.7 mm, the output displacement decreases from 0.543 to 0.237 μm. The safe selection range ensures the design requirement is from 0.3 to 0.5 mm with 0.1 steps.

Then, the value of variable $t$ and the $\alpha$ is fixed. The displacement output and stress output were analyzed to consider the best value of $l$. Figure 4 shows the value of output displacement. The length of the flexure hinge is increased from 3 to 8 mm. The minimum displacement amplification ratio is 0.520 μm at $l = 7$ mm; the maximum is 0.543 μm at $l = 5$ mm. The range of parameters selected for $l$ is 4, 5, and 6 mm.

Finally, the variable incline angle $\alpha$ is observed while the value of variable $t$ and $l$ is fixed. The displacement output and stress output were analyzed to consider the best value of $\alpha$. The $\alpha$ has changed within 0.9° to 1.5°. As the angle increases, the output displacement gain decreases, as shown in Figure 5. The three highest outputs are selected as design parameters for the flexure hinge mechanism. The design parameters of $\alpha$ are 1°, 1.1°, and 1.2°.

### 3.3 Design simulation

The Taguchi experimental design involves three factors with three levels; L27 orthogonal arrays were used to conduct the simulation. The levels of each factor are shown in Table 2. The observed responses are displacement of the output of one side of the microgripper function in the $x$-axis and stress within the model. Table 3 shows the experimental layout and results.

#### 3.4 Grey relational analysis method

The Grey theory [42] is widely applied to the system whose model is uncertain or lacks information. It supplies an effective solution to the problem of uncertainty and multiple discrete inputs. GRA based on Grey theory is well-known for its suitability about solving multiple factors (Morán, Granada, Míguez, & Porteiro) [43]. GRA was useful to analyze a variety of MADM problems (Olson & Wu) [44]. The initial problem is to reduce the issue into single-property decision-making, similar with the procedure applied in TOPSIS, integrating all properties values into a single value. The first step of the GRA process is called Grey rationalization, which normalizes the input value from 0 to 1 for testing data. Then, in the second step, based on the normalized experimental data, we calculate the Grey relation coefficients to represent the correlation between the desirable data and actual experimental data. At the final, we calculate the average GRC of selected

### Table 2 Material mechanical properties

| Factor               | Levels |       |       |
|----------------------|--------|-------|-------|
|                      | Levels | 1     | 2     | 3     |
| Incline angle of FXH (degree) |        | 1     | 1.1   | 1.2   |
| Length of FXH (l, mm)       |        | 4     | 5     | 6     |
| Thickness of FXH (t, mm)    |        | 0.3   | 0.4   | 0.5   |
cases to determine the overall Grey relation grade. The Grey relation grade can indicate the impact performance and characteristic of parameters during the multi-response process. Then, based on the signal-to-noise (S/N) ratio of the Taguchi method, the parameter configuration with the highest GRG can be considered as the optimal solution for the case and determine the quality characteristics.

The equation for the S/N ratio is shown in Eq. (1):  

\[
\text{S/N} = 10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right) \tag{1}
\]

In this study, the GRA is used to analyze the multi-response characteristics in the optimization procedure. The steps are shown as below:

Step 1. Normalize data  
The smaller-the-better case is computed as

\[
x_i^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{2}
\]

The larger-the-better case is computed as

\[
x_i^*(k) = 1 - \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{3}
\]

And the normalized-the-better case is computed as

\[
x_i^*(k) = 1 - \frac{x_i^0(k) - x_0}{\max x_i^0(k) - x_0} \tag{4}
\]

Following the requirement in this study, the stress was chosen as “smaller-the-better.” The displacement was chosen as the “larger-the-better.”

\[
x_i^*(k) = \sum_{j=1}^{k} \Delta x_j^0(k) - x_0 \]

where the distinguishing coefficient (\(\zeta \in [0, 1]\)) used to tune the relation coefficient. Its value was chosen as 0.5, and the stress was computed using Eq. (3). Step 2. GRC calculation  
The connection with the ideal and the actual experiment results is shown as GRC \(\xi_i(k)\), which is calculated by Eq. (5):

\[
\xi_i = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_{ai}(k) + \zeta \Delta_{max}} (0 < \xi_i(k) \leq 1) \tag{5}
\]

where \(\Delta_{ai}(k)\) is the deviation array of reference array \(x_i^0(k)\) and comparability array \(x_i^*(k)\):

\[
\Delta_{ai} = \left| x_i^*(k) - x_i^0(k) \right| \tag{6}
\]

\[
\Delta_{min} = \min_{j \in k} \left| x_j^0(k) - x_i^0(k) \right| \tag{7}
\]

\[
\Delta_{max} = \max_{j \in k} \left| x_j^0(k) - x_i^0(k) \right| \tag{8}
\]

\(\zeta\) is the distinguishing coefficient \((\zeta \in [0, 1])\) used to tune up the difference of the relational coefficient. Its value was chosen as 0.5, the and the stress was computed using Eq. (3).

Step 3. GRG is computed by averaging the corresponding Grey relational coefficients:

\[
\gamma_i = \frac{\sum_{k=1}^{k} w_k \varphi_i^*(k)}{\sum_{k=1}^{k} w_k} \tag{9}
\]

where \(w_k\) is the normalized weight of element \(k\) according to the real situation of various factor.
3.5 Entropy method

Using the probability theory, we can formulate and determine uncertain information (Wen et al. [45]). The entropy method can be used to derive the weights and the entropy \((E_j)\), which are calculated by the following equations.

Step 1. Calculate the summation of each attribute’s value for all array, \(D_k\) (Sum of the GRC in all sequences):

\[
D_k = \sum_{i=1}^{n} x_i(k)
\]  (10)

Step 2: Figure out the entropy of the specific attribute, \(e_k\):

\[
e_k = K \sum_{i=1}^{m} W e(P_i) = \frac{1}{(e^{0.5} - 1) * m}
\]  (13)

Step 3. Calculate the total entropy value \(E\):

\[
E = \sum_{k=1}^{n} e_k
\]  (14)

Step 4. Determine the relative weighting factor, \(\beta_k\):

\[
\beta_k = \frac{1}{n - E} (1 - e_k)
\]  (15)

Step 5. The normalized weight of each attribute can be calculated by:

\[
w_k = \frac{\beta_k}{\sum_{k=1}^{n} \beta_k}
\]  (16)

3.6 TOPSIS method

The TOPSIS (Lai et al.) [46] is one of the classical multi-criteria decision matrix (DMs) methods as developed by Hwang and Yoon [47]. TOPSIS, be advantage of its capacity to define the best alternative rapidly, is an attractive ranking technique that only requires limited thematic input. In order to appreciate the distance between data series, the decision matrix in the TOPSIS process is formed by the Grey coefficients in this study. The TOPSIS method is shown in Eq. (17) [47]:

Step 1. The DMs is presented as the below matrix:

\[
A = (a_{ij})_{mn} = \begin{bmatrix}
a_{11} & a_{12} & \ldots & a_{1n} \\
a_{21} & a_{22} & \ldots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{m1} & a_{m2} & \ldots & a_{mn}
\end{bmatrix}
\]  (17)

where \(n\) is the quantity of variables and \(a_{ij}\) is the value of GRC.

The equation is used to normalize each attribute value \(a_{ij}\) in DMs \(A = (a_{ij})_{mn}\) into a correlate factor \(g_{ij}\) in a normalized DMs as

\[
G = (g_{ij})_{mn} = \begin{bmatrix}
g_{11} & g_{12} & \ldots & g_{1n} \\
g_{21} & g_{22} & \ldots & g_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
g_{m1} & g_{m2} & \ldots & g_{mn}
\end{bmatrix}
\]  (18)

where

\[
g_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} (a_{ij})^2}}, i \in \{1, 2, \ldots, m\}, j \in \{1, 2, \ldots, n\}
\]  (19)

Step 2. Calculate the weighted standardized DMs:

\[
z = (w_jg_{ij})_{mn}
\]  (20)

where the weights \((w_j)\) are calulated by the entropy method [45].

Step 3. Calculate the positive ideal solution (PIS, \(D^+\)) and negative ideal solution (NIS, \(D^-\)).

\[
D^+ = \{z_1^+, z_2^+, \ldots, z_i^+\}, z_i^+ = \max_{1 \leq i \leq m} z_{ij}, j \in N
\]  (21)

\[
D^- = \{z_1^-, z_2^-, \ldots, z_i^-\}, z_i^- = \min_{1 \leq i \leq m} z_{ij}, j \in N
\]  (22)

Step 4. Calculate the root-mean-square error (RMSE) of target position with positive ideal (PI) position and negative ideal (NI) position by using the Euclidean distance.

The derived PIS \(S_i^+\) is shown as follows:

\[
S_i^+ = \sqrt{\sum_{i=1}^{m} (z_{ij} - z_{ij}^+)^2}, i \in \{1, 2, \ldots, m\}
\]  (23)

The derived NIS \(S_i^-\) is shown as follows:

\[
S_i^- = \sqrt{\sum_{i=1}^{m} (z_{ij} - z_{ij}^-)^2}, i \in \{1, 2, \ldots, m\}
\]  (24)

where \(S_i^+\) and \(S_i^-\) can be also considered as the distances of the \(i^{th}\) alternative with PI and NI solution.

Step 5. Calculate the coefficient closest to the ideal solutions.

The nearness coefficient of the \(i^{th}\) alternative \(D_i\) with correlation to the ideal solution is shown as
Step 6. The ranking order and valuation. The priority of alternatives can be sorted in descending order according to $C_i$; the higher $C_i$ implies the better choice.

### 3.7 Hybrid GTs-TOPSIS method

The hybrid optimization method can simplify the data processing procedure and time reduction and provide the user to determine a more efficient method to select the most appropriate criteria. For example, it revealed DM problem in a fuzzy-covered approximation space and solved it by the TOPSIS method [48]. First, integrating a fuzzy proximity operator with a fuzzy coarse set model, two pairs of fuzzy coarse set models based on overlapping and studying basic characteristics together with the classification of these two pairs of models. Then, a new method specifies the target weights using a pair of fuzzy coarse models based on the first overlay. In order to solve the material selection problem, take advantage of the fuzzy rough set in processing uncertain data and the method of determining objective criteria weights with TOPSIS, integrating both methods to propose a new multi-criteria decision-making method [49]. The combination of fuzzy and TOPSIS method has been studied and used as the right decision tool for choosing the optimal solution to the problems of selecting robots and rapid prototyping in production.

TOPSIS is an attractive ranking technique, whose advantage is the ability to identify the best alternative faster with just limited subject input. In this study, the Grey coefficients are used to build up the decisions-making matrix in the TOPSIS procedure to evaluate the range between the data chain. The calculation process is shown in Figure 6.

### 4 Results and discussion

#### 4.1 Grey relational grade: Taguchi (GTs)

We first normalize the initial data values to the range of values [0-1]; the feedback value of the chosen displacement amplifier is as large as possible and the smaller the better for stress value. We normalized data results using Eqs. (1) and (2). Next, the deviation sequences $\Delta_0i$ are calculated by Eqs. (5)–(7). The result calculations are presented in Table 4.

Then, the distinguishing coefficient $\zeta$ is used to adjust the range of the comparison environment, which can be substituted for the Grey relational coefficient in Eq. (4); in this study, $\zeta$ is taken as 0.5. The last step is to determine the Grey relational grade coefficient, based on Eq. (8), the Grey relational grade coefficient has been determined, and the results are presented in Table 5. In this study, the weight of each factor after applying the formula in the entropy method [45] is 0.5002 and 0.4998, respectively. The larger GRG makes the performance characteristics possible. Figure 7 and Table 5 show that Experiment 1 had the highest GRG of 0.726 among experiments. Thus, Experiment 1 demonstrated the best performance among the 27 experiments. At Experiment 1 with flexure hinge geometry parameters, the thickness is 0.3 mm, the length is 4 mm, and the incline angle is 1°. The large output amplifier displacement ratio is 58 times; the stress is 2.4316 MPa.

\[
C_i = \frac{S_{i}^{-}}{S_{i}^{-} + S_{i}^{+}}, i \in \{1, 2, \ldots, m\}
\]
Calculate the S/N ratio to analyze the optimal level for each parameter \( t \), \( l \), and \( \alpha \), respectively. The optimal configuration of the flexure hinge dimension parameters was observed as \( l_1t_1\alpha_1 \). The results are shown in Table 6. The main effects and interaction plot for mean for GRG are shown in Figure 8. In Figure 8, this graph can be used to graphically evaluate each input process parameter. As the value analyzed by the main effects and interaction plot, input parameters such as thickness, length, and incline angle are significant at their first level, while the higher values have no significant effect on output displacement of the asymmetrical microgripper. Additionally, the parameter that has the most influence on the output response is the thickness with the maximum deviation, which is calculated as the difference between the highest and lowest values of the graph. The large difference indicates a more robust effect of this parameter than the rest of the parameters.

The means of GRG are shown in Table 7. The optimal parametric combination is chosen based on the higher mean GRG. Hence, the best combination values for maximizing the multiple performance characteristics were the thickness of 0.3 mm, the length of 4 mm, and the incline angle of 1°.

![Fig. 7 Results of Grey relational grade (GRG) of the experiments](image)
Analysis of variance (ANOVA) output of the multiple performance characteristics is given in Table 8. The referred confidence and significance levels were 0.95 and 0.05, respectively.

As shown in Table 8, the thickness and incline angle of the flexure hinge are remarkable factors, and the interaction of the thickness with the incline angle also has significant value. Thickness has the largest contribution ratio as 72.73% to the flexure hinge. Furthermore, the contributions of incline angle and length are 14.78% and 3.04%, respectively. Thus, the variation of thickness of flexure hinge will significantly affect the displacement amplifier based on the preferred criteria output.

\[ R^2 \] was calculated as 97.12%, which can be considered as the suitability of this linear regression model.

### 4.2 Combine GTs-TOPSIS

The first step was to classify the attributes and alternatives as the parameter inputs and response outputs of the experiment. Its values are substituted into the GRC, placed to decision matrix A.

Decision matrix A and matrix G were normalized by Eqs. (17) and (18). Besides, Eq. (19) can be used to compute the benefit attribute. The value of two attributes is inversely proportional which \( t \) means when one of the attributes decreased, the other will increase. Additionally, the value of change is the same. In this paper, the benefit attribute was used for analysis, and the entropy method was applied to specify the attribute weight by using Eqs. (10)–(16) sequentially. The results are shown in Table 9. Matrix Z was calculated by Eq. (20) with attribute weight \( w_j = [0.5002 \ 0.4998]^T \).

In the next step, Eqs. (21) and (22) are used to determine the positive and negative ideal solutions. Then, the nearest alternative ranges from PIS and the farthest alternative range from NIS were computed by Eqs. (23) and (24). The nearest coefficient is calculated by using Eq. (24). Finally, alternatives according to the value of \( C_i \) were selected. The largest \( C_i \) was the best choice. The resulting values are shown in Table 10. According to the below result, the highest closeness coefficient was observed at the Experiment 1, meaning it was the nearest to the ideal value.

The optimal parameter was verified at \( l_1, t_1, \alpha_1 \). The Taguchi technique was proposed to find the greatest value. The result is shown in Table 11.

The S/N ratio data and the mean data provided the same optimal level by drawing the main effects plot. The result is shown in Figure 9.
The main effects and interaction plot for mean for GTs-TOPSIS are shown in Figure 10. Similar to the results of GRG analysis, the new integrated hybrid method gives results consistent with the GRG results. The factor that has the most influence on the output displacement is the thickness of the FHs.

Analysis of variance output of the multiple performance characteristics is given in Table 12. As shown in Table 12, it shows that the thickness and incline angle of the flexure hinge are remarkable factors. The thickness of the flexure hinge had the biggest contribution at 71.18%. Hence, the length of flexure hinge had the most significant impact on

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F value | P value |
|--------|----|--------|--------------|--------|--------|---------|---------|
| α      | 2  | 0.0937 | 14.78%       | 0.0937 | 0.0469 | 20.53   | 0.001   |
| l      | 2  | 0.0193 | 3.04%        | 0.0193 | 0.0096 | 4.22    | 0.056   |
| t      | 2  | 0.4613 | 72.73%       | 0.4613 | 0.2307 | 101.04  | 0.000   |
| α*l    | 4  | 0.0179 | 2.82%        | 0.0179 | 0.0045 | 1.96    | 0.194   |
| α*t    | 4  | 0.0206 | 3.25%        | 0.0206 | 0.0052 | 2.26    | 0.152   |
| l*t    | 4  | 0.0032 | 0.50%        | 0.0032 | 0.0008 | 0.35    | 0.837   |
| Error  | 8  | 0.0183 | 2.88%        | 0.0183 | 0.0023 |         |         |
| Total  | 26 | 0.6343 | 100.00%      |        |        |         |         |

R-sq 97.12%

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Table 8 Analysis of variance (ANOVA) result

Table 9 Decision matrix

No. Matrix A Matrix G Matrix Z = (w_jp_i)_{max}  
   GRC Attribute GRC Attribute GRC Attribute  
| | Displacement | Stress | | Displacement | Stress | | Displacement | Stress |  
|---|-------------|--------|---|-------------|--------|---|-------------|--------|  
| 1 | 0.9955      | 0.9545 | 0.2994 | 0.3222 | 0.4979 | 0.4771 |  
| 2 | 0.4701      | 1.0000 | 0.1414 | 0.3376 | 0.1667 | 0.3055 |  
| 3 | 0.3333      | 0.6112 | 0.1003 | 0.2063 | 0.2672 | 0.4907 |  
| 4 | 0.5343      | 0.9817 | 0.1607 | 0.3314 | 0.2430 | 0.2960 |  
| 5 | 0.4858      | 0.5922 | 0.1461 | 0.1999 | 0.1718 | 0.2994 |  
| 6 | 0.3434      | 0.5990 | 0.1033 | 0.2022 | 0.4687 | 0.3892 |  
| 7 | 0.9370      | 0.7787 | 0.2818 | 0.2629 | 0.2443 | 0.2788 |  
| 8 | 0.4884      | 0.5579 | 0.1469 | 0.1883 | 0.1740 | 0.2749 |  
| 9 | 0.3478      | 0.5500 | 0.1046 | 0.1857 | 0.5002 | 0.2530 |  
| 10| 1.0000      | 0.5062 | 0.3008 | 0.1709 | 0.2434 | 0.2458 |  
|11 | 0.4866      | 0.4919 | 0.1464 | 0.1600 | 0.2361 | 0.3071 |  
|12 | 0.3436      | 0.6144 | 0.1034 | 0.2074 | 0.4696 | 0.2117 |  
|13 | 0.9929      | 0.4235 | 0.2986 | 0.1430 | 0.2515 | 0.2462 |  
|14 | 0.5028      | 0.4926 | 0.1512 | 0.1663 | 0.1772 | 0.2376 |  
|15 | 0.3543      | 0.4753 | 0.1066 | 0.1604 | 0.4691 | 0.2196 |  
|16 | 0.9380      | 0.4393 | 0.2821 | 0.1483 | 0.2526 | 0.2300 |  
|17 | 0.5050      | 0.4602 | 0.1519 | 0.1553 | 0.1795 | 0.2265 |  
|18 | 0.3589      | 0.4531 | 0.1080 | 0.1530 | 0.4862 | 0.1666 |  
|19 | 0.9721      | 0.3333 | 0.2924 | 0.1125 | 0.2486 | 0.1960 |  
|20 | 0.4970      | 0.3921 | 0.1495 | 0.1324 | 0.1762 | 0.2304 |  
|21 | 0.3524      | 0.4609 | 0.1060 | 0.1556 | 0.4817 | 0.1731 |  
|22 | 0.9630      | 0.3463 | 0.2897 | 0.1169 | 0.2565 | 0.1728 |  
|23 | 0.5127      | 0.3458 | 0.1542 | 0.1167 | 0.1817 | 0.2168 |  
|24 | 0.3632      | 0.4338 | 0.1092 | 0.1464 | 0.4564 | 0.1782 |  
|25 | 0.9126      | 0.3566 | 0.2745 | 0.1204 | 0.2573 | 0.2156 |  
|26 | 0.5144      | 0.4313 | 0.1547 | 0.1456 | 0.1840 | 0.2476 |  
|27 | 0.3679      | 0.4954 | 0.1107 | 0.1672 | 0.1840 | 0.2476 |  

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the displacement amplifier based on the preferred configuration output. The contribution of the length and incline angle was 3.37% and 15.66%, respectively. \( R^2 \) is figured out as 96.53%, which indicated that this linear regression model was suitable for 96.53% of data set.

### 5 Experiment and confirmation test

#### 5.1 Confirmation simulation test

A demonstration was conducted to verify the quality of the output response. The forecast optimized value was calculated by Eq. (26):

![Main effects plot for mean and S/N ratios](image)

#### Table 10 Nearness coefficient value and alternative ranking

| S. No. | \( S_i^+ \) | \( S_i^- \) | \( C_i \) | Rank |
|--------|-------------|-------------|--------|------|
| 1      | 0.0228      | 0.4540      | 0.9521 | 1    |
| 2      | 0.2650      | 0.3402      | 0.5621 | 5    |
| 3      | 0.3860      | 0.1389      | 0.2646 | 14   |
| 4      | 0.2331      | 0.3393      | 0.5928 | 3    |
| 5      | 0.3281      | 0.1502      | 0.3140 | 11   |
| 6      | 0.3847      | 0.1329      | 0.2567 | 15   |
| 7      | 0.1150      | 0.3751      | 0.7654 | 2    |
| 8      | 0.3381      | 0.1364      | 0.2875 | 12   |
| 9      | 0.3962      | 0.1085      | 0.2150 | 20   |
| 10     | 0.2468      | 0.3445      | 0.5826 | 4    |
| 11     | 0.3612      | 0.1103      | 0.2339 | 17   |
| 12     | 0.3807      | 0.1406      | 0.2697 | 13   |
| 13     | 0.2882      | 0.3330      | 0.5360 | 6    |
| 14     | 0.3552      | 0.1163      | 0.2466 | 16   |
| 15     | 0.4160      | 0.0717      | 0.1470 | 24   |
| 16     | 0.2820      | 0.3070      | 0.5212 | 7    |
| 17     | 0.3662      | 0.1067      | 0.2256 | 18   |
| 18     | 0.4213      | 0.0612      | 0.1269 | 26   |
| 19     | 0.3335      | 0.3195      | 0.4893 | 9    |
| 20     | 0.3945      | 0.0870      | 0.1806 | 22   |
| 21     | 0.4214      | 0.0645      | 0.1327 | 25   |
| 22     | 0.3272      | 0.3150      | 0.4905 | 8    |
| 23     | 0.4078      | 0.0900      | 0.1807 | 21   |
| 24     | 0.4261      | 0.0524      | 0.1095 | 27   |
| 25     | 0.3245      | 0.2900      | 0.4719 | 10   |
| 26     | 0.3739      | 0.1030      | 0.2159 | 19   |
| 27     | 0.4044      | 0.0828      | 0.1700 | 23   |

#### Table 11 S/N ratio of GTS-TOPSIS.

| Level | Parameter | Incline angle | Length | Thickness |
|-------|-----------|---------------|--------|-----------|
| 1     | Incline angle | −4.182       | −4.782 | −2.666 |
| 2     | Incline angle | −5.463       | −5.559 | −5.907 |
| 3     | Incline angle | −6.188       | −5.492 | −7.26   |

![Interaction plot for means (GTS-TOPSIS)](image)
where $\eta_{tm}$ is the average value of whole response, $\eta_i$ is the average value of the response at the best level, and $r$ is the quantity of input parameters. The result of the confirmatory experiment is shown in Table 13.

In Table 13, the initial parameters from the design requirements are the incline angle of the flexing hinge at 1.2°, the length of the flexing hinge 5 mm, and the thickness of the flexing hinge 0.4 mm. The optimum parameters determined by GRA and Grey-TOPSIS have the same values as the angle of inclination of the flexing hinge 1°, the length of the flexing hinge 4 mm, and the thickness of the flexing hinge of 0.3 mm. However, the analytical results show that the estimated coefficient following the Grey-TOPSIS method is much more robust compared with using the GRA method. The feedback on the improved displacement amplifier is using this recommended method.

### 5.2 Prototype of the microgripper

The parameter of the sample is taken from the optimal result shown in the Table 5. The optimal geometry parameter of the model is an incline angle of 1°, the length of 4 mm, and the thickness of 0.3 mm, respectively. To simplify the fabrication manufacturing process and reduce costs, the sample was fabricated by 3D printer. The material is PLA. The prototyping model is shown in Figure 11.

### 5.3 Experiment and measuring process

To verify the performance of the asymmetric microgripper mechanism, it is necessary to perform tests on the micro-clamp device. The devices applied to the experiment are listed as in Table 14. The experiment system consists

$$\eta_{predict} = \eta_{im} + \sum_{i=1}^{r} (\eta_i - \eta_{im})$$

(26)

where $\eta_{im}$ is the average value of whole response, $\eta_i$ is the average value of the response at the best level, and $r$ is the quantity of input parameters. The result of the confirmatory experiment is shown in Table 13.

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### Table 12 Analysis of variance (ANOVA) result

| Source   | DF | Seq SS | Contribution | Adj SS | Adj MS | F value | P value |
|----------|----|--------|--------------|--------|--------|---------|---------|
| $\alpha$ | 2  | 0.18796| 15.66%       | 0.18795| 0.09397| 18.07   | 0.001   |
| $l$      | 2  | 0.04044| 3.37%        | 0.04043| 0.02021| 3.89    | 0.066   |
| $t$      | 2  | 0.85409| 71.18%       | 0.85409| 0.42704| 82.1    | 0       |
| $\alpha^*l$ | 4 | 0.04096| 3.41%        | 0.04096| 0.01024| 1.97    | 0.192   |
| $\alpha^*t$ | 4 | 0.02885| 2.40%        | 0.02884| 0.00721| 1.39    | 0.321   |
| $l^*t$   | 4  | 0.00601| 0.50%        | 0.00600| 0.00150| 0.29    | 0.877   |
| Error    | 8  | 0.04161| 3.47%        | 0.04161| 0.00520|         |         |
| Total    | 26 | 1.19992| 100.00%      |        |        |         |         |
| S        | R-sq | R-sq(adj)| PRESS | R-sq(pred)| 0.072124| 96.53% | 88.73% | 0.474017 | 60.50% |

### Table 13 Initial, predicted, and compared evaluation test

| Level | Initial | Optimal parameter | GRA | Grey-TOPSIS |
|-------|---------|-------------------|-----|-------------|
|       | Prediction | Test | Prediction | Test  |
| $\alpha$ | 1.2 | 1 | 1 |  |
| $l$    | 5   | 4   | 4   |  |
| $t$    | 0.4 | 0.3 | 0.3 |  |
| C      | 0.1807 | 0.7695 | 0.9521 |  |
| GRG    | 0.4293 | 0.859 | 0.975 |  |
| Improvement | 0.4297 | 0.5457 | 0.588 | 0.771 |

$$\eta_{predict} = \eta_{im} + \sum_{i=1}^{r} (\eta_i - \eta_{im})$$

(26)

where $\eta_{im}$ is the average value of whole response, $\eta_i$ is the average value of the response at the best level, and $r$ is the quantity of input parameters. The result of the confirmatory experiment is shown in Table 13.

In Table 13, the initial parameters from the design requirements are the incline angle of the flexing hinge at 1.2°, the length of the flexing hinge 5 mm, and the thickness of the flexing hinge 0.4 mm. The optimum parameters determined by GRA and Grey-TOPSIS have the same values as the angle of inclination of the flexing hinge 1°, the length of the flexing hinge 4 mm, and the thickness of the flexing hinge of 0.3 mm. However, the analytical results show that the estimated coefficient following the Grey-TOPSIS method is much more robust compared with using the GRA method. The feedback on the improved displacement amplifier is using this recommended method.

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### 5.3 Experiment and measuring process

To verify the performance of the asymmetric microgripper mechanism, it is necessary to perform tests on the micro-clamp device. The devices applied to the experiment are listed as in Table 14. The experiment system consists

### Table 14 Experiment device list

| A   | DPO 2014B digital oscilloscope |
|-----|--------------------------------|
| B   | Analog amplifier SVR 150/3     |
| C   | PST controller PI              |
| D   | DC power supply GP C-60300     |
| E   | Laser head LB12(W)             |
| F   | Laser amplifier reader LB-72(W)|
| G   | Probe sensor                   |
| H   | PST 150                        |
mainly of a controlled power source, PZT servo controller, analog amplifier, a piezoelectric actuator, a laser measuring device, and an asymmetric microgripper mechanism, as illustrated in Figure 12.

The value of measuring comparison is taken from the mean of the three measurements. The input displacement of the structure is changed from 0 to 40 μm corresponding to 0 V to 150 V of the output amplifier controller. The input

**Fig. 12** Experimental layout diagram of the microgripper mechanism. a Principle diagram connection. b Experiment setup
voltage control of the amplifier is from 0 to 5 V. In this case, we observed 10 points with the input displacement from 4 to 40 μm with the pitch at 4. The resolution of the laser sensor is 0.4 V/mm. Therefore, we can calculate the displacement output of the microgripper. The measurement result is shown in Table 15.

In Table 14, based on the resolution of equipment, we can obtain the displacement output corresponding to the displacement input. The value of the output displacement based on the experiment was compared with the simulation value. The result shown in the ratio amplifier of the structure of microgripper is approximately 58.4 times. The initial instability of the measurement signal is 0–6 μV. The maximum error of the signal measurement is 101 μm/2000 μm compared with the simulation result. The error is 4.8%. This result is acceptable. The comparison of results is shown in Figure 13.

From Figure 11, it can be seen that the output displacement of the experiment is linearly related to the output simulated value, indicating that the microgripper has stable performance.

### 6 Conclusions
Based on the idea of the triple-stair structure of the flexure hinge mechanism and overcoming the disadvantage of symmetrical clamping, a new asymmetric microgripper structure was designed using a piezoelectric actuator. The model has been designed to apply the TSBM; thus, the rigidity of the model increased. In addition, it can withstand larger input forces than the single and double-staircase structures. Furthermore, it still ensures the output amplifier displacement ratio is the largest. First, the model is designed based on Inventor software. Then, we conduct simulation analysis based on the finite element analysis method in ANSYS software. Then, experiments were designed involving three factors with three levels using the orthogonal array L27. The output responses were observed such as displacement of the output of the one side of the microgripper function in the x-axis and stress within the model.

**Table 15** Result of measurement and analysis

| No | Output voltage(V) | Displacement PST (μm) | Mean value of Laser signal measurement (mV) | Mean (mV) | Displacement output experiment (μm) | Displacement output Simulation(μm) | Error (%) |
|----|-------------------|-----------------------|---------------------------------------------|-----------|-------------------------------------|------------------------------------|----------|
| 1  | 15                | 4                     | 91.31                                       | 93.7      | 92.5                                | 231.2                              | 232.7    | 0.7      |
| 2  | 22.5              | 8                     | 181.53                                      | 186.29    | 183.9                               | 459.68                             | 467.2    | 1.6      |
| 3  | 30                | 12                    | 274.92                                      | 282.11    | 278.5                               | 696.32                             | 699.9    | 0.5      |
| 4  | 45                | 16                    | 367.31                                      | 376.93    | 372.1                               | 930.24                             | 929.1    | 0.1      |
| 5  | 60                | 20                    | 456.45                                      | 468.40    | 462.50                              | 1156                               | 1168.8   | 1.1      |
| 6  | 75                | 24                    | 544.50                                      | 558.76    | 551.72                              | 1379.04                            | 1401.5   | 1.6      |
| 7  | 90                | 28                    | 615.38                                      | 631.49    | 623.53                              | 1558.56                            | 1636.0   | 4.7      |
| 8  | 105               | 32                    | 721.69                                      | 740.58    | 731.26                              | 1827.84                            | 1870.4   | 2.3      |
| 9  | 120               | 36                    | 790.50                                      | 811.19    | 800.97                              | 2001.92                            | 2103.2   | 4.8      |
| 10 | 150               | 40                    | 880.72                                      | 903.77    | 892.39                              | 2230.4                             | 2337.6   | 4.6      |

**Fig. 13** The output displacement comparison between simulation and experiment
This paper presented a new integrated method of the Grey-TOPSIS and entropy weight to determine the best dimension configuration to achieve the maximum output displacement ratio. The proposed optimization method is useful to apply to microgripper design, compliance mechanisms, and complex engineering optimization problems. The results obtained the highest output displacement ratio with the following design parameters: the incline angle (α) is 1°, the length (l) is 4 mm, and the thickness (t) is 0.3 mm. The input displacement ratio is 0.01 mm, the largest output displacement result is 0.5818 mm, the amplification ratio is 58 times, and the stress after the analysis is 2.432 MPa. The model of this paper can be applied in the assembly of micro-components with dimension from 0 to 581 μm.

In future work, the kinetic analysis can be used to describe and analyze in-depth the performance of the flexure hinge with different geometrical parameters on the microgripper mechanism. Further investigation of stiffness and natural frequency analysis of the microgripper mechanism can be conducted. It is hoped that the proposed model can be used in the assembly process of micro-components, providing a useful reference for studying multi-stage amplification manipulators and microgrippers.

Data availability All data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Content to participate Not applicable.

Content to publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

1. Zhong Y, Shirinzadeh B, Alici G, Smith J (2006) Soft tissue modelling through autowaves for surgery simulation. Med Biol Eng Comput 44(9):805. https://doi.org/10.1007/s11517-006-0084-7
2. Zimmermann S, Tiemerding T, Fatikow S (2015) Automated robotic manipulation of individual colloidal particles using vision-based control. IEEE/ASME Trans Mechatron 20(5):2031–2038. https://doi.org/10.1109/TMECH.2014.2361271
3. Carrozza MC, Eisinberg A, Menciassi A, Campolo D, Micera S, Dario P (2000) Towards a force-controlled microgripper for assembling biomedical microdevices. J Micromech Microeng 10(2):271–276. https://doi.org/10.1088/0960-1317/10/2/328
4. Rakotondrabe M, Ivan IA (2011) Development and force/position control of a new hybrid thermo-piezoelectric micro gripper dedicated to micromanipulation tasks. IEEE Trans Autom Sci Eng 8(4):824–834. https://doi.org/10.1109/TASE.2011.2157683
5. Gu G, Zhu L, Su C, Ding H, Fatikow S (2015) Proxy-based sliding-mode tracking control of piezoelectric-actuated nanopositioning stages. IEEE/ASME Trans Mechatron 20(4):1956–1965. https://doi.org/10.1109/TMECH.2014.2360416
6. Qin Y, Shirinzadeh B, Tian Y, Zhang D (2013) Design issues in a decoupled XY stage: static and dynamics modeling, hysteresis compensation, and tracking control. Sens Actuators, A 194:95–105. https://doi.org/10.1016/j.sna.2013.02.003
7. Tian Y, Shirinzadeh B, Zhang D (2009) A flexure-based mechanism and control methodology for ultra-precision turning operation. Precis Eng 33(2):160–166. https://doi.org/10.1016/j.precisioneng.2008.05.001
8. Somà A, Jamoni S, Voicu R, Müller R, Al-Zandi M, Wang C (2018) Design and experimental testing of an electro-thermal microgripper for cell manipulation. Microsyst Technol 24(2):1053–1060. https://doi.org/10.1007/s00542-017-3460-3
9. Nachiippam NM, Venkatesh AP, Muniyappan M (2018) Modelling and analysis of piezoelectric microgripper for unmanned aerial vehicle. Maters Today: Proc 5(9, Part 3):19456–19462. https://doi.org/10.1016/j.mtpr.2018.06.306
10. Haddab Y, Chaillet N, Bourjault A (2000, 31 Oct.-5 Nov. 2000) A microgripper using smart piezoelectric actuators. Paper presented at the Proceedings. 2000 IEEE/RSJ Int Conf Intelligent Robots and Syst (IROS 2000) (Cat. No.00CH37113). https://doi.org/10.1109/IROS.2000.894679
11. Long Z, Zhang J, Liu Y, Han C, Li Y, Li Z (2017) Dynamics modeling and residual vibration control of a piezoelectric gripper during wire bonding. IEEE Transactions on Components, Packaging and Manufacturing Technology 7(12):2045–2056. https://doi.org/10.1109/TPCMPT.2017.2723458
12. Sreekumar M, Nagarajan T, Singaperumal M, Zoppi M, Molinero R (2007) Critical review of current trends in shape memory alloy actuators for intelligent robots. Industrial Robot: An International Journal 34:285–294. https://doi.org/10.1108/10506920710887726
13. Nonaka K, Sakai K, Bailleul J (2004, 4–6 Aug. 2004) Open loop oscillatory control for electromagnetic actuated microgrippers. Paper presented at the SICE 2004 Annual Conf ISBN:4–907764–22–7
14. Despa V, Catangiu A, Ivan IA, Gurgu V, Ardeleanu M (2014) Modeling and control of a microgripper based on electromagnetic actuation. Paper presented at the Scientific Bulletin of VALAHIA University – Materials and Mechanics 60(12):103298. https://doi.org/10.1016/j.jnonlinmech.2013.103298
15. Alnemyaz A, Khater M, Abdel-Aziz A, Heppler G, Abdel-Rahman E (2020) Electrostatic arch micro-tweezers. Int J Non-Linear Mech 118:103298. https://doi.org/10.1016/j.jnonlinmech.2020.103298
16. Chen W, Zhang X, Fatikow S (2016) A novel microgripper hybrid driven by a piezoelectric stack actuator and piezoelectric cantilever actuators. Rev Sci Instrum 87(11):115003. https://doi.org/10.1063/1.4967218
17. Shi B, Wang F, Huo Z, Tian Y, Zhao X, Zhang D (2018, 13–17 Aug. 2018) Design and characteristics of a novel compliant symmetric microgripper mechanism. Paper presented at the 2018 IEEE Int Conf Manipulation, Manuf Measurement on the Nanoscale (3M-NANO). https://doi.org/10.1109/3M-NANO.2018.8552246
18. Jain R, Majumder S, Ghosh B, Saha S (2015) Design and manufacturing of mobile micro manipulation system with a compliant piezoelectric actuator based micro gripper. J Manuf Syst. https://doi.org/10.1016/j.jmsy.2014.12.001
19. Liaw HC, Shirinzadeh B, Smith J (2008) Sliding-mode enhanced adaptive motion tracking control of piezoelectric actuation systems for micro/nano manipulation. IEEE Trans Control Syst Technol 16(4):826–833. https://doi.org/10.1109/TCST.2007.916301
Das TK, Shirinzadeh B, Al-Jodah A, Zhong Y, Smith J (2020) Design, analysis and experimental investigations of a high precision flexure-based microgripper for micro/nano manipulation. Mechatronics 69:102396. https://doi.org/10.1016/j.mechatronics.2020.102396

Bao L, Zhou X (2014) Design of micro-gripper with two-stage amplifier for micro-assembly and its experimental research. Machine Design and Research 30(1):47–50. https://doi.org/10.13952/cnki.jofmrd.2014.01.012

Chen G, Ma Y, Li J (2016) A tensural displacement amplifier employing elliptic-arc flexure hinges. Sens Actuators, A 247:307–315. https://doi.org/10.1016/j.sna.2016.05.015

Chen X, Deng Z, Hu S, Gao J, Gao X (2019) Design of a flexible piezoelectric microgripper based on combined amplification principles. Nanotechnology and Precision Engineering 2(3):138–143. https://doi.org/10.1007/j.ntepe.2019.10.006

Sun X, Chen W, Fatikow S, Tian Y, Zhou R, Zhang J, Mikczinski M (2015) A novel piezo-driven microgripper with a large jaw displacement. Microsyst Technol 21(4):931–942. https://doi.org/10.1007/s00542-014-2199-3

Wang F, Liang C, Tian Y, Zhao X, Zhang D (2016) Design and control of a compliant microgripper with a large amplification ratio for high-speed micro manipulation. IEEE/ASME Trans Mechatron 21(3):1262–1271. https://doi.org/10.1109/TMECH.2016.2523564

Koo B, Hong S, Kim S, Kang C, Han S, Oh K, Kim Y (2015) Design and application of a novel in situ nano-manipulation stage for transmission electron microscopy. Microsc Microanal 21:1–9. https://doi.org/10.1017/S1431927615000239

Xing Q (2015) Design of asymmetric flexible micro-gripper mechanism based on flexure hinges. Adv Eng Mech 7(6):1687814015590331. https://doi.org/10.1177/1687814015590331

Chen W, Zhang X, Li H, Wei J, Fatikow S (2017) Nonlinear analysis and optimal design of a novel piezoelectric-driven compliant microgripper. Mech Mach Theory 118:32–52. https://doi.org/10.1016/j.mechmachtheory.2017.07.011

Ho N, Dao T, Chau N, Huang S (2019) Multi-objective optimization design of a compliant microgripper based on hybrid teaching learning-based optimization algorithm. Microsyst Technol. https://doi.org/10.1007/s00542-018-4222-6

Xiao S, Li Y, Zhao X (2011, 17–19 Sept. 2011) Optimal design of a novel micro-gripper with completely parallel movement of gripping arms. Paper presented at the 2011 IEEE 5th Int Conf Robotics, Automation and Mechatronics (RAM). https://doi.org/10.1109/RAMECH.2011.6070452

Verotti M, Di Giambardino P, Belfiore NP, Giannini O (2019) A genetic algorithm-based method for the mechanical characterization of biosamples using a MEMS microgripper: numerical simulations. J Mech Behav Biomed Mater 96:88–95. https://doi.org/10.1016/j.jmbbm.2019.04.023

Gok A (2015) A new approach to minimization of the surface roughness and cutting force via fuzzy TOPSIS, multi-objective grey design and RSA. Measurement 70:100–109. https://doi.org/10.1016/j.measurement.2015.03.037

Tiwary AP, Pradhan BB, Bhattacharyya B (2014) Application of multi-criteria decision making methods for selection of micro-EDM process parameters. Advances in Manufacturing 2(3):251–258. https://doi.org/10.1007/s40436-013-0050-1

Wang C, Tu S, Chen M, Yuan Y (2016) Optimal selection of a longwall mining method for a thin coal seam working face. Arab J Sci Eng 41(9):3771–3781. https://doi.org/10.1007/s13369-016-2260-x

Roy MK, Ray A, Pradhan BB (2014) Non-traditional machining process selection using integrated fuzzy AHP and QFD techniques: a customer perspective. Production & Manufacturing Research 2(1):530–549. https://doi.org/10.1080/21693277.2014.938276

Arun P, Avanish D (2013) Modeling and optimization of kerf taper and surface roughness in laser cutting of titanium alloy sheet. J Mech Sci Technol. https://doi.org/10.1007/s12206-013-0527-7

Şengül E, Shiraz E, Gezder, & Şengül. (2015) Fuzzy TOPSIS method for ranking renewable energy supply systems in Turkey. Renewable Energy 75:617–625. https://doi.org/10.1016/j.renene.2014.10.045

Liu S, Forrest J, Yang Y (2011, 15–18 Sept. 2011) A brief introduction to grey systems theory. Paper presented at the Proceedings of 2011 IEEE Int Conf Grey Systems and Intelligent Services. https://doi.org/10.1109/GSIS.2011.6044018

Morán J, Granada E, Miguez JL, Porteiro J (2006) Use of grey relational analysis to assess and optimize small biomass boilers. Fuel Process Technol 87:123–127. https://doi.org/10.1016/j.fuproc.2005.08.008

Olson D, Wu D (2006) Simulation of fuzzy multiattribute models for grey relationships. Eur J Oper Res 175:111–120. https://doi.org/10.1016/j.ejor.2005.05.002

Wen KL, Chang TC, You ML (1998, 14–14 Oct. 1998) The grey entropy and its application in weighting analysis. Paper presented at the SMC’98 Conference Proceedings. 1998 IEEE Int Conf Sys, Man, and Cybernetics (Cat. No.98CH36218). ISBN: 0-7803-4778-1

Lai YJ, Liu T, Chiu Y, Hwang CL (1994) TOPSIS for MODM. Eur J Oper Res 65:222–228. https://doi.org/10.1016/0377-2217(94)90367-0

Hwang CL, Yoon K (1981) Methods for multiple attribute decision making, in: multiple attribute decision making. Lecture Notes in Economics and Mathematical Systems, vol 186. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-48318-9_3

Zhang K, Zhan J, Yao Y (2019) TOPSIS method based on a fuzzy covering approximation space: an application to biological nano-materials selection. Inf Sci 502:297–329. https://doi.org/10.1016/j.ins.2019.06.043

Vahdani B, Mousavi SM, Tavakkoli-Moghaddam R (2011) Group decision making based on novel fuzzy modified TOPSIS method. Appl Math Model 35(9):4257–4269. https://doi.org/10.1016/j.apm.2011.02.040

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