Research Article

Optimal Design of a Novel Rescue Accessory with Spreading and Supporting Functions

Chunrong Wang, Erdong Xia, Kun-Chieh Wang, and Changjiong Xiong

School of Mechanical and Electric Engineering, Sanming University, Sanming 365004, Fujian, China

Correspondence should be addressed to Kun-Chieh Wang; m18316252102@126.com

Received 17 March 2022; Accepted 25 April 2022; Published 21 May 2022

Academic Editor: Laxminarayan Sahoo

Copyright © 2022 Chunrong Wang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

A novel rescue accessory with spreading and supporting functions is proposed to promote the performance of usage continuity and improve the rescue efficiency of traditional rescue devices. To optimally design this rescue device, we apply related working principles to analyze the motion of the whole device and its spreading mechanism. In optimization, three important parameters of the spreading width, the jaw rotation angle, and the spreading force are simultaneously chosen as the objective functions. Meanwhile, specific mathematical models are established for estimating the performance of the novel rescue accessory. Then, an improved algorithm based on the nondominated sorting genetic algorithm (INSGA-II) is proposed to solve the above multi-objective optimization problem of the rescue accessory. The INSGA-II optimizes the population diversity, the crossover operator, and the mutation operation in calculation procedures. Furthermore, it can dynamically adjust the crowded distance and enhance the global as well as the local searching capabilities of INSGA-II. Results from computational tests show that INSGA-II has the best performance among other popular algorithms. More importantly, comparison results show that the compromise solution of the Pareto front for the above three objective functions obtained by INSGA-II is superior to those by other algorithms.

1. Introduction

Earthquake is a sudden and destructive natural disaster. Once happened, it usually brings about huge damages and casualties to humankind due to its unpredictability [1, 2]. Therefore, earthquake defenses and rescue operations have always been the focus of governments around the world [3,4]. Researches on the high-performance earthquake rescue equipment become very important.

In recent years, the rescue robot played an important role in the postdisaster rescue status [5, 6]. This is because it can enter the narrow space of a building to carry out rescue actions. Bai et al. [7] designed a transformable wheel-legged mobility rescue robot that can be switched between the wheel and leg functions to adapt to different terrains. Deng et al. [8] proposed a control strategy based on rolling gait and trajectory planning, which might enable the hexapod robot to walk through dynamic environments and complete rescue missions. Zhang and Gao [9] designed a mine rescue robot with a head mechanism of the groundhog-like and studied its mobility and inverse kinematics. In addition, the structure and motion parameters of the hybrid head mechanism were optimized, and the optimal dexterity was obtained. Li et al. [10] designed a tracked rescue robot with an explosion-proof multidrive crawler and a lightweight explosion-proof body support system. Zang et al. [11] designed a cutting robot and a Jack robot to carry out works of cutting obstacles and jacking up heavy debris. However, in general, the rescue robot is too small to cross large obstacles and provide enough applying force. That is why this kind of robot is usually used to carry out detection rather than rescue missions.

On the other hand, the machinery of large-scale rescue equipment and general large-scale construction equipment played an important role in the postdisaster rescue [12, 13]. However, after the earthquake, roads and bridges are often interrupted, and it is difficult to transport the large-scale rescue equipment to the quake-stricken area over a long distance and perform in-time (within the golden 72 hours) rescue. To overcome this problem, lots of general large-scale
construction equipment were designed and proposed with features of economic production and simple construction. And, they may reach the disaster area as quickly as possible. However, due to the lack of specialized rescue accessories such as an end-effector, their functions are still limited, and they cannot be effectively used to perform deeper rescue missions [14, 15].

For rescue equipment, some specific rescue accessories with proper functions are essential in performing different specific rescue missions. For example, in the postearthquake rescue scene, when there is a gap in the ruin, we may overcome it by using a spreader which may help to expand the whole rescue equipment to a proper height [16, 17]. Then, the supporting accessory can be used to support or further expand, so as to complete the rescue operation [18, 19]. In short, due to limited space at the rescue scene, it is difficult to accommodate large-scale construction machinery to perform rescue operations. Therefore, spreading and supporting rescue accessories are essential and commonly used in rescue operations.

As regards, in this paper, we intend to design a novel rescue accessory with spreading and supporting functions, which can be quickly docked with general large-scale construction equipment. Then, to better solve the optimal design problem for this accessory, an improved algorithm is proposed based on the nondominated sorting genetic algorithm (NSGA-II) [20] which has been widely used in the field of multiobjective optimization [21–23].

The remainder of the paper is structured as follows. Section 2 describes the integration of spreading and supporting functions, and the working principle of the proposed novel rescue accessory. The kinematics analysis of the spreading mechanism is made, and the multiobjective optimization problem for the accessory is formulated in Section 3. An improved strategy of NSGA-II is proposed, and a comparison of algorithm performance is made in Section 4. Results and discussions are drawn in Section 5. The conclusions of this work are given in Section 6.

2. Novel Design of Rescue Accessory with Spreading and Supporting Functions

2.1. Mechanism. As mentioned above, the spreading and supporting functions are often required in rescue operations. In order to perform these two operations coherently so as to improve the rescue efficiency, we innovatively design a rescue accessory with spreading and supporting functions, as shown in Figure 1. The designed rescue accessory consists of a spreading hydraulic actuator, two supporting hydraulic actuators, two translational hydraulic actuators, a spreading mechanism, and a supporting mechanism. The spreading and supporting forces are provided by a translational hydraulic actuator and two supporting hydraulic actuators, respectively. This rescue accessory may be quickly docked with general large-scale construction machinery, and its hydraulic power is supplied from the construction machinery.

2.2. Working Principle. During rescuing, if the gap in the ruin is small, we may use the spreading mechanism first to expand this gap, as shown in Figure 2(a). Then, we use the
supporting mechanism to support or further expand the gap, as shown in Figure 2(b). During the spreading operation, the supporting and translational hydraulic actuators must be retracted to the preset limit positions and then locked. In addition, the supporting actuator must be aligned in parallel with the translational hydraulic actuator so as not to interfere with the spreading operation, as shown in Figure 2(a). When the spreading mechanism expands the gap size to a sufficient extent, we may then adjust and lock the supporting hydraulic actuator at an appropriate angle to perform the supporting operation, as shown in Figure 2(b).

3. Kinematics Analysis and Problem Formulation

The spreading mechanism plays an important role in the rescue accessory. Its maximum spreading width and bearing load directly determine the whole rescue efficiency. Therefore, in this section, the kinematics analysis of the spreading mechanism will be made. The spreading width, jaw rotation angle, and spreading force are chosen as the objective functions.

3.1. Kinematics Analysis of Spreading Mechanism

Due to geometric symmetry, only half of the spreading mechanism is shown here in Figure 3, which majorly consists of a four-bar linkage. For clear visualization, the supporting mechanism is hidden. The linkage FD and the axis of symmetry are used as the base to construct a rectangular coordinate system for describing motions. The ith linkage and its length are represented by the vector notation \( \mathbf{L}_i \) and \( l_i \), respectively. The initial and final positions of the spreading mechanism are shown in black and blue vector lines, respectively. The vector loop closure equations for the initial and final positions are expressed as follows:

\[
\begin{aligned}
\mathbf{L}_{2i} + \mathbf{L}_3 &= \mathbf{L}_4 + \mathbf{L}_1, \\
\mathbf{L}_{2f} + \mathbf{L}_3 &= \mathbf{L}_4 + \mathbf{L}_1.
\end{aligned}
\]

(1)

Related angles between each link and AD are shown in Figure 4. Then, we may deduce that

\[
\begin{aligned}
l_2 e^{i\theta_{3i}} + l_3 e^{i\theta_{3i}} - l_4 e^{i\theta_{3i}} - l_1 e^{j\theta_0} &= 0, \\
l_2 e^{i\theta_{3f}} + l_3 e^{i\theta_{3f}} - l_4 e^{i\theta_{3f}} - l_1 e^{j\theta_0} &= 0,
\end{aligned}
\]

(2)

where \( j \) is the imaginary unit.

In addition, (2) can be rewritten based on the Eulerian formulation, as follows:

\[
\begin{aligned}
l_3 \cos(\theta_{3i}) - l_4 \cos(\theta_{4i}) - l_1 &= 0, \\
l_2 + l_3 \sin(\theta_{3i}) - l_4 \sin(\theta_{4i}) &= 0, \\
l_3 \cos(\theta_{3f}) - l_4 \cos(\theta_{4f}) - l_1 &= 0, \\
l_2 + l_3 \sin(\theta_{3f}) - l_4 \sin(\theta_{4f}) &= 0.
\end{aligned}
\]

(3)

By solving (3), we can obtain

\[
\begin{aligned}
\theta_{3i} &= 2 \cdot \arctan \left( \frac{A_1 + \sqrt{A_1^2 + B_1^2 - C_1^2}}{B_1 - C_1} \right), \\
\theta_{4i} &= \arcsin \left( \frac{l_2 + l_3 \sin(\theta_{3i})}{l_4} \right), \\
\theta_{3f} &= 2 \cdot \arctan \left( \frac{A_2 + \sqrt{A_2^2 + B_2^2 - C_2^2}}{B_2 - C_2} \right), \\
\theta_{4f} &= \arcsin \left( \frac{l_2 + l_3 \sin(\theta_{3f})}{l_4} \right).
\end{aligned}
\]

(4)
where $A_1 = 2l_2l_3$, $B_1 = B_2 = -2l_1l_3$, $C_1 = l_1^2 + l_2^2 + l_3 - l_4^2$, $A_2 = 2l_2l_3$, and $C_2 = l_1^2 + l_2^2 + l_3 - l_4^2$.

### 3.2. Mathematical Model of Spreading Width and Jaw Rotational Angle

As known, the efficiency of spreading can be improved when the spreading width becomes large. To enlarge the spreading width, the projection length in the initial and final positions of link 5 on the X-axis should be as long as possible. Here, we investigate three cases of the spreading mechanism with different linkage lengths in the initial and final positions, as shown in Figure 5. For these cases, we can get

$$l_6 = l_5 \sin \left( \frac{\theta_{5i} - \pi}{2} \right),$$

where

$$\theta_{5i} = \arcsin \left( \frac{l_6}{l_5} \right) + \frac{\pi}{2}.$$

For all three cases of different spreading widths, it is observed that the angle between the linkage 5 and the linkage 3 always remains at a fixed value. This means that this angle of the spreading mechanism in the initial position is equal to that in the final position. Therefore, for the first case, we may obtain that

$$\theta_{5i} - \theta_{3i} = \theta_{5f} - \theta_{3f}, \quad \theta_{3i} > 0, \theta_{3f} > 0.$$  (7)

For the second case, we obtain that

$$\theta_{5i} - \theta_{3i} = \theta_{5f} - \theta_{3f}, \quad \theta_{3i} > 0, \theta_{3f} < 0.$$  (8)

For the third case, we obtain that

$$\theta_{5i} - \theta_{3i} = \theta_{5f} - \theta_{3f}, \quad \theta_{3i} < 0, \theta_{3f} < 0.$$  (9)

In total, we have

$$d = l_6 + l_5 \cos \theta_{5f},$$

where $d$ is the spreading width and $\theta_{jaw}$ is the rotational angle of the jaw.

### 3.3. Mathematical Model of Spreading Force

According to the geometric relationship of the spreading mechanism shown in Figure 5, we can easily derive that

$$\theta_{5f} = \theta_{5i} - \theta_{3i} + \theta_{3f},$$

where $\theta_{5f}$ is the angle between the linkage 5 and the linkage 3 in the final position, and $\theta_{3f}$ is the angle between the linkage 3 and the jaw in the final position.

According to the force distribution for a spreading operation of the accessory, we assume that the force on the tip of the spreading mechanism is perpendicular to the axis of symmetry during the spreading operation. And, the thrust of the spreading hydraulic actuator is denoted as $F_t$, and the pressure at the point $E'$ is $F_p$. The mechanical stability is a
necessary condition in spreading operations of rescue missions. We now assume the system is under an equilibrium state during the spreading operation. Thus,

\[ \begin{align*}
\sum F_X &= 0, \\
\sum F_y &= 0, \\
\sum M(D) &= 0.
\end{align*} \tag{12} \]

From (12), we obtain

\[ F_s = \frac{F_t (l_1 + l_5 \sin(\theta_{5i} - \pi/2))}{l_{2f} + l_5 \sin(\theta_{5f})}. \tag{13} \]

Similarly, we can find that the spreading force is also a function of the length of each linkage. Here, the thrust of the spreading hydraulic actuator is set as \( F_t = 200kN \).

3.4. Multiobjective Optimization Formulation. As stated above, the spreading mechanism must not only be able to move between the initial and final positions but also have the largest possible spreading width and force. However, a large spreading width is always accompanied by a large rotational angle of the jaw. With the increase of jaw rotational angle, the contact area between the jaw tips and the object gradually decreases, which makes the spreading operation more unstable and is prone to secondary collapse. That is, the spreading width and jaw rotational angle have an opposite relationship. Therefore, our target is to maximize the spreading width and the spreading force and minimize the jaw rotational angle. Thus, three objectives are defined as

\[ \begin{align*}
\max (f_1 (X) = d), \\
\max (f_2 (X) = F_s), \\
\min (f_3 (X) = \theta_{jaw}).
\end{align*} \tag{14} \]

where \( X \) is the design variable which is defined as

\[ X = [x_1, x_2, x_3, x_4, x_5, x_6, x_7]^T = [l_1, l_2, l_3, l_4, l_5, l_6]^T. \tag{15} \]

As previously stated, the motion of the four-bar linkage is driven by the spreading hydraulic actuator. Although the length of each linkage is determined at the initial design stage, it should be carefully chosen, not just simply being greater than zero or arbitrarily. In order to enhance the calculation speed and avoid excluding possible optimal solutions, we set the upper and lower bounds of the design variables based on the actual working conditions as
\begin{align*}
40 \leq x_1 & \leq 200, \\
40 \leq x_2 & \leq 80, \\
50 \leq x_3 & \leq 150, \\
40 \leq x_4 & \leq 200, \\
60 \leq x_5 & \leq 240, \\
240 \leq x_6 & \leq 300, \\
20 \leq x_7 & \leq 30.
\end{align*} 

In addition, a four-bar linkage mechanism can be well constructed by properly selecting different design variables. The suggested restrictions for the lengths of linkages are

\begin{align}
&l_1 + l_2(l_{2f}) + l_3 - l_4 \geq 0, \\
&l_1 + l_2(l_{2f}) - l_3 + l_4 \geq 0, \\
&l_1 - l_2(l_{2f}) + l_3 + l_4 \geq 0, \\
&-l_1 + l_3(l_{3f}) + l_3 + l_4 \geq 0.
\end{align}

As shown in Figure 4, when the spreading mechanism moves to the final position, the spreading hydraulic actuator must extend upward, and the linkage BE must expand to the right side. Then, the \(l_{2f}, \theta_{3i}, \text{and } \theta_{3j}\) are restricted as

\begin{align}
&l_{2f} - l_{3j} \geq 0, \\
&\theta_{3i} - \theta_{3f} \geq 0.
\end{align}

In many encountering rescue cases, the gap is usually very small, so we expect that the initial spreading width of the spreading mechanism should be as small as possible. Therefore, the \(\theta_{3i}\) is restricted as

\begin{equation}
\theta_{3i} \leq 2\pi - \frac{2\pi}{3} \geq 0.
\end{equation}

In addition, in (4), since the angles \(\theta_{3i}\) and \(\theta_{3j}\) cannot be imaginary numbers, these two angles should satisfy the following requirements:

\begin{align}
&A_1^2 + B_1^2 - C_1^2 \geq 0, \\
&A_2^2 + B_2^2 - C_2^2 \geq 0.
\end{align}

4. Methodology

On the basis of the so-called “genetic algorithm (GA)” [24, 25], the traditional NSGA-II is a popular method for solving multiobjective optimization problems [20]. However, in practical applications, the NSGA-II has the defects of being prone to premature convergence and having a non-uniform distribution of the Pareto solution set. To improve its defects so as to successfully apply to our study, we propose an improved strategy of NSGA-II which modifies the crowded distance, the crossover operator, and the mutation operation that appeared in traditional NSGA-II. The followings are the details of INSGA-II.

4.1. Improving Crowded Distance. The sorting strategy of NSGA-II is based on the individual crowded distance. The crowded distance is used to estimate the density of solutions around a particular individual in the population. The crowded distance of the \(i\)th individual is the sum of the distances between two neighboring individuals in its layer for each object. In the same layer, the individual with a large crowded distance will be preferred. Although this strategy retains individuals within a small crowded distance, it has some limitations. Since the crowded distance is only calculated once if multiple individuals with a small crowded distance are concentrated in a certain region, these individuals will be deleted at the same time.

To solve the above-mentioned problem, a dynamically adjusting method of the crowded distance is proposed as follows.

Step 1. Calculate the Euclidean distance between two adjacent individuals. Assuming there are \(n\) individuals, the crowded distance between the \(k^{th}\) and \((k+1)^{th}\) individuals, \(k \in (2, n-1)\), can be expressed as

\begin{equation}
d(k, k+1) = \sqrt{\sum_{i=1}^{m} \left( f_i(k) - f_{i_{\text{min}}} - f_i(k+1) - f_{i_{\text{max}}} \right)^2 },
\end{equation}

where \(m\) is the number of objective functions, \(f_i(k)\) is the value of the \(k^{th}\) individual on the \(i^{th}\) object, \(f_{i_{\text{min}}}\) is the minimum value of the \(i^{th}\) objective function, and \(f_{i_{\text{max}}}\) is the maximum value of the \(i^{th}\) objective function.

Step 2. Find the minimum crowded distance \(d(k, k+1)\) and compare \(d(k-1, k)\) with \(d(k+1, k)\). If \(d(k-1, k)\) is small, then the \(k^{th}\) individual is eliminated; otherwise, the \((k+1)^{th}\) individual is eliminated.

Step 3. Update the crowded distance. Determine whether to meet the number of individuals required. If it is not satisfied, return to Step 2, otherwise, terminate.

4.2. Improving Crossover Operator. Traditional NSGA-II adopts the simulated binary crossover in generating an individual’s offspring. This operation has limited ability in dealing with the optimization problem with complex Pareto fronts, such as slow convergence and low accuracy.

In order to improve the global searching capability of NSGA-II, the normal-distribution crossover is introduced. The normal distribution crossover operator is defined as

\begin{equation}
c_{i/2} = \frac{\left( y_{1i} + y_{2i} \right) \pm 1.481 \cdot \left| N(0, 1) \right| (y_{1i} - y_{2i})}{2},
\end{equation}

where \(c_{i/2}\) is the \(i^{th}\) crossover variable for the offspring chromosome, \(y_{1i}\) and \(y_{2i}\) are the \(i^{th}\) crossover variables for two parental chromosomes, and \(N(0, 1)\) is a normally distributed random variable.

To further enhance the spatial-searching capability of NSGA-II, we introduce a discrete recombination operation to the previous normal distribution crossover operator, as follows:
4.3. Improving Mutation Operation. To improve the local-searching capability of NSGA-II, a cross-mutation algorithm based on the close relative coefficient is proposed. Firstly, we define two variables: the close relative coefficient and the close relative individuals.

**Definition 1.** The close relative coefficient of two individuals is defined as

\[
F(X_i, X_j) = \frac{\sum_{k \in \{0, 1\}, x_{ik} = x_{jk}} \mu_k}{\sum_{k \in \{0, 1\}} \mu_k},
\]

where \( l \) is the length of the individual gene, \( x_{ik} \) is the \( k \)th gene of the individual \( X_i \), and \( \mu_k \) is the weight of the \( k \)th allele.

**Definition 2.** If the close relative coefficient of two individuals is greater than the set threshold, the two individuals are considered to be close relative individuals.

Secondly, the implementation process of this proposed cross-mutation algorithm is as follows:

1. Select two parent individuals \( X_i \) and \( X_j \) randomly, and find the same allelic set \( N_s \) and different allelic set \( N_d \) of these two individuals.
2. Calculate the close relative coefficient to determine whether the two parents are close relatives. If so, go back to Step (1); otherwise, go to Step (3).
3. The genes in \( N_s \) are transferred to offspring individuals, and \( l - |N_s| \) genes are randomly selected from gene set \( N_d \) to offspring individuals.
4. According to the number of the same allele, calculate the number of mutation genes. The calculation formula is as follows:

\[
c_{i/2j} = \begin{cases} 
\frac{(y_{1i} + y_{2j}) \mp 1.481|N(0, 1)|}{2} & \mu \leq 0.5, \\
\frac{(y_{1i} + y_{2j}) \mp 1.481|N(0, 1)|}{2} & \mu > 0.5, 
\end{cases}
\]

where \( \mu \) is a uniformly distributed random number on the interval \((0, 1)\).

\[
N_v = \frac{|N_s| - 1}{3} + 1,
\]

where \( N_v \) is the number of mutation genes.

Step 5. Calculate the probability of mutation based on the number of the same allelic genes and the current number of iterations \( G_i \). The calculation formula is as follows:

\[
P_v = \frac{(l - |N_s|)}{l} a + \frac{1}{1 + e^{G_{max} - G_i / G_{max}}},
\]

where \( G_{max} \) is the total number of iterations, and \( a \in [0, 1] \).

Step 6. Perform mutation operation according to the number of mutation genes and the probability of mutation.

### Table 1: Parameters used for different algorithms.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SPEA2</th>
<th>PESSAII</th>
<th>NSGA-II</th>
<th>INSGA-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population size</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Maximum number of generations</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Probability of crossover</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>-</td>
</tr>
<tr>
<td>Probability of mutation</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>Crossover operator</td>
<td>binary</td>
<td>Improved crossover</td>
<td>Simulated crossover</td>
<td></td>
</tr>
<tr>
<td>Mutation operator</td>
<td>Gauss mutation</td>
<td>Improved mutation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Figure 7: Pareto front of ZDT1 obtained by different algorithms.
\[ GD = \frac{1}{n} \left( \sum_{i=1}^{n} d_i^2 \right)^2, \]
\[ SP = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (\bar{d} - d_i)^2} \]

where \( n \) is the number of individuals in the Pareto front, \( d_i \) is the Euclidean distance between the \( i^{th} \) objective function vector in the Pareto solution set and the nearest individual in the true Pareto solution set, and \( \bar{d} \) is the average of \( d_i \). All four algorithms are now running 30 times independently, and the obtained data are then averaged. The obtained simulation results are given in Table 2.

It is found in Table 2 that the mean values of \( GD \) and \( SP \) obtained by INSGA-II are smaller than those of the other three algorithms. In other words, INSGA-II has
Figure 12: Pareto front of DTLZ1 obtained by different algorithms.

Figure 13: Pareto front of DTLZ2 obtained by different algorithms.

Figure 14: Pareto front of DTLZ3 obtained by different algorithms.
better convergence and uniformity. In addition, when using the test functions of ZDT2 and ZDT3, the standard deviation of GD and SP obtained by INSGA-II is smaller than those of the other three algorithms; that is, this method has better robustness. Specifically, the simulation results were obtained via any of the aforementioned algorithms, adopting ZDT3 as the test function, which usually has a noncontinuous Pareto front distribution. It is seen that the distribution performance of the Pareto front for INSGA-II is better than those for the other three algorithms when using ZDT3 as the test function. In short, the test results indicate that the proposed INSGA-II has significant improvement in calculation convergence and results from consistency when compared with other traditional algorithms.

5. Results and Discussions

5.1. Optimization Analysis with Different Methods. We now perform the optimization analysis for our designed spreading mechanism using INSGA-II, traditional NSGA-II, PESAII, and SPEA2 methods with the related fundamental parameters as shown in Table 1. This multiobjective optimization problem of the spreading mechanism has been already defined in Section 3.4. Through calculations, we obtain the distributions of the Pareto front using the above four methods, as shown in Figure 15.

Since it is difficult to observe the distribution of the solution set in the three-dimensional space, we now extract and compare the data of extreme values of obtained objective functions, the maximum $f_1$, the maximum $f_2$, and the minimum $f_3$, for better understanding, as shown in Table 3. The comparison shows that the Pareto front distribution obtained by INSGA-II is more uniform than those obtained by the other algorithms. And, larger $f_1$ and $f_2$ and smaller $f_3$ occur in the case by using INSGA-II than those by using the other algorithms. This proves that INSGA-II has better population diversity and global and local search abilities and can provide more suitable solutions for designers to choose.

5.2. Comparison of the Compromise Solutions. In solving our multiobjective optimization problem of the designed rescue device, there always exists some contradiction between objects. These usually lead to different solution qualities of

<table>
<thead>
<tr>
<th>Functions</th>
<th>Algorithms</th>
<th>GD Mean</th>
<th>GD Standard deviation</th>
<th>SP Mean</th>
<th>SP Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZDT1</td>
<td>INSGA-II</td>
<td>3.1423E-3</td>
<td>2.5047E-5</td>
<td>4.1038E-2</td>
<td>5.0113E-3</td>
</tr>
<tr>
<td></td>
<td>NSGA-II</td>
<td>1.0561E-2</td>
<td>2.2239E-5</td>
<td>5.3025E-1</td>
<td>2.1205E-2</td>
</tr>
<tr>
<td></td>
<td>SPEA2</td>
<td>8.8201E-2</td>
<td>3.9802E-5</td>
<td>5.0026E-1</td>
<td>1.9985E-2</td>
</tr>
<tr>
<td>ZDT2</td>
<td>INSGA-II</td>
<td>2.3315E-3</td>
<td>3.5539E-6</td>
<td>5.3064E-2</td>
<td>6.3158E-3</td>
</tr>
<tr>
<td></td>
<td>NSGA-II</td>
<td>4.9482E-3</td>
<td>4.0952E-5</td>
<td>5.4469E-1</td>
<td>1.1862E-2</td>
</tr>
<tr>
<td></td>
<td>PESAII</td>
<td>3.8809E-2</td>
<td>3.0238E-5</td>
<td>8.5274E-1</td>
<td>3.0512E-2</td>
</tr>
<tr>
<td>ZDT3</td>
<td>INSGA-II</td>
<td>4.0217E-3</td>
<td>2.0874E-5</td>
<td>1.2504E-2</td>
<td>1.0257E-2</td>
</tr>
<tr>
<td></td>
<td>NSGA-II</td>
<td>7.0287E-3</td>
<td>2.2140E-5</td>
<td>3.1571E-1</td>
<td>1.6507E-2</td>
</tr>
<tr>
<td></td>
<td>SPEA2</td>
<td>5.2287E-2</td>
<td>3.6678E-5</td>
<td>5.6412E-1</td>
<td>3.5842E-2</td>
</tr>
<tr>
<td></td>
<td>PESAII</td>
<td>5.4107E-2</td>
<td>5.8921E-5</td>
<td>8.6641E-1</td>
<td>4.1530E-2</td>
</tr>
<tr>
<td>ZDT4</td>
<td>INSGA-II</td>
<td>2.6484E-3</td>
<td>1.8054E-4</td>
<td>2.4651E-2</td>
<td>1.8191E-2</td>
</tr>
<tr>
<td></td>
<td>NSGA-II</td>
<td>3.0529E-2</td>
<td>1.9951E-4</td>
<td>5.1966E-1</td>
<td>1.8535E-2</td>
</tr>
<tr>
<td>ZDT6</td>
<td>INSGA-II</td>
<td>1.0211E-3</td>
<td>3.3231E-4</td>
<td>4.6601E-2</td>
<td>2.0211E-2</td>
</tr>
<tr>
<td></td>
<td>SPEA2</td>
<td>1.5974E-1</td>
<td>5.3393E-4</td>
<td>1.3195E-1</td>
<td>6.6541E-2</td>
</tr>
<tr>
<td>DTLZ1</td>
<td>INSGA-II</td>
<td>4.5233E-3</td>
<td>1.8861E-4</td>
<td>2.8021E-2</td>
<td>4.2174E-2</td>
</tr>
<tr>
<td></td>
<td>SPEA2</td>
<td>2.83061</td>
<td>5.5986E-1</td>
<td>6.21751</td>
<td>4.3521E-2</td>
</tr>
<tr>
<td></td>
<td>PESAII</td>
<td>9.58091</td>
<td>8.4057E-1</td>
<td>8.08241</td>
<td>5.6201E-2</td>
</tr>
<tr>
<td>DTLZ2</td>
<td>INSGA-II</td>
<td>8.4254E-3</td>
<td>4.0214E-3</td>
<td>1.6105E-2</td>
<td>5.5520E-2</td>
</tr>
<tr>
<td></td>
<td>NSGA-II</td>
<td>1.3355E-2</td>
<td>6.6062E-3</td>
<td>1.8868E-1</td>
<td>3.0247E-2</td>
</tr>
<tr>
<td></td>
<td>SPEA2</td>
<td>2.8815E1</td>
<td>3.6514E-1</td>
<td>2.55721</td>
<td>4.3521E-2</td>
</tr>
<tr>
<td></td>
<td>PESAII</td>
<td>1.7981E1</td>
<td>4.5519E-1</td>
<td>3.65881</td>
<td>5.6201E-2</td>
</tr>
<tr>
<td>DTLZ3</td>
<td>INSGA-II</td>
<td>1.1324E-3</td>
<td>3.0254E-3</td>
<td>1.0881E-1</td>
<td>5.6635E-3</td>
</tr>
<tr>
<td></td>
<td>NSGA-II</td>
<td>3.7765E-3</td>
<td>4.4604E-3</td>
<td>2.9202E-1</td>
<td>2.1127E-2</td>
</tr>
<tr>
<td></td>
<td>SPEA2</td>
<td>5.6053E1</td>
<td>6.1534E-1</td>
<td>9.8008E1</td>
<td>3.3024E-2</td>
</tr>
<tr>
<td></td>
<td>PESAII</td>
<td>5.0862E1</td>
<td>3.7730E-1</td>
<td>3.8405E1</td>
<td>3.8174E-2</td>
</tr>
</tbody>
</table>
the Pareto set for each objective function. However, it is difficult for designers to observe and select suitable solutions from Pareto set in the multidimensional space. A method for converting the Pareto set from the multidimensional space to the two-dimensional space was proposed by Walker [28]. In the two-dimensional space, these solutions are mapped into corresponding points restricted to a specific polygon. Also, the vertices of this polygon are determined from the following formula:

\[ V_p = \begin{bmatrix} \cos \left( \frac{2\pi (i-1)}{I} \right) \\ \sin \left( \frac{2\pi (i-1)}{I} \right) \end{bmatrix} \quad i = 1, 2, \ldots I, \]  

where \( I \) is the number of objectives. These points are further mapped by

\[
\begin{align*}
    f_1 &= \frac{1}{2} \left( f_{1,\text{max}} + f_{1,\text{min}} \right) + \frac{1}{2} \left( f_{1,\text{max}} - f_{1,\text{min}} \right) \cos \left( \frac{2\pi (i-1)}{I} \right) \\
    f_2 &= \frac{1}{2} \left( f_{2,\text{max}} + f_{2,\text{min}} \right) + \frac{1}{2} \left( f_{2,\text{max}} - f_{2,\text{min}} \right) \sin \left( \frac{2\pi (i-1)}{I} \right)
\end{align*}
\]

Table 3: Comparison of extremums of objective functions.

<table>
<thead>
<tr>
<th>Algorithms</th>
<th>( f_1 ) (mm)</th>
<th>( f_2 ) (KN)</th>
<th>( f_3 ) (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INSGA-II</strong></td>
<td>( f_{1,\text{max}} )</td>
<td>270.00</td>
<td>199.03</td>
</tr>
<tr>
<td></td>
<td>( f_{2,\text{max}} )</td>
<td>269.99</td>
<td>199.99</td>
</tr>
<tr>
<td></td>
<td>( f_{3,\text{min}} )</td>
<td>30.00</td>
<td>137.12</td>
</tr>
<tr>
<td><strong>NSGA-II</strong></td>
<td>( f_{1,\text{max}} )</td>
<td>269.05</td>
<td>181.44</td>
</tr>
<tr>
<td></td>
<td>( f_{2,\text{max}} )</td>
<td>269.05</td>
<td>181.44</td>
</tr>
<tr>
<td></td>
<td>( f_{3,\text{max}} )</td>
<td>74.28</td>
<td>131.34</td>
</tr>
<tr>
<td><strong>SPEA2</strong></td>
<td>( f_{1,\text{max}} )</td>
<td>214.89</td>
<td>113.99</td>
</tr>
<tr>
<td></td>
<td>( f_{2,\text{max}} )</td>
<td>124.10</td>
<td>132.40</td>
</tr>
<tr>
<td></td>
<td>( f_{3,\text{min}} )</td>
<td>89.89</td>
<td>129.11</td>
</tr>
<tr>
<td><strong>PESAII</strong></td>
<td>( f_{1,\text{max}} )</td>
<td>221.94</td>
<td>116.46</td>
</tr>
<tr>
<td></td>
<td>( f_{2,\text{max}} )</td>
<td>123.57</td>
<td>132.68</td>
</tr>
<tr>
<td></td>
<td>( f_{3,\text{min}} )</td>
<td>85.41</td>
<td>128.73</td>
</tr>
</tbody>
</table>

Figure 15: Pareto fronts of different algorithms. (a) INSGA-II. (b) NSGA-II. (c) SPEA2. (d) PESAII.
\[
P_j = \frac{\sum_{i=1}^{I} f'_{j,i} V_{P_i}}{\sum_{i=1}^{I} f'_{j,i}} \quad j = 1, 2, \ldots, J, \quad (29)
\]

where \(f'_{j,i}\) is the normalized value of solution \(f\)’s \(i^{th}\) objective, \(I\) is the number of solutions in the Pareto front.

In order to observe the characteristics of these points more clearly, we mark them with different colors by the following formula:

\[
c = \sum_{i=1}^{I} f'_{j,i} \quad (30)
\]

Then, the Pareto fronts obtained by different algorithms may be mapped into two-dimensional spaces, as shown in Figure 16. Blue and yellow points represent the minimum and maximum of \(c\), respectively. If a point is closer to the vertex, it indicates that the value of the corresponding objective function is better, and the values of other objective functions are worse. The point closest to the center of the polygon has the same performance for each objective function, which is defined as the compromise solution. Eventually, the compromise solutions by different algorithms are obtained as shown in Figure 16 and Table 4.
6. Conclusion

For improving the efficiency of traditional rescue equipment, a novel rescue accessory with spreading and supporting functions is proposed in this paper. The working principle for the main components of the rescue accessory is discussed, and the kinematics analysis of the spreading mechanism is made. In analysis, the spreading width, jaw rotational angle, and spreading force are simultaneously chosen as the objective functions, and some mathematical models are established for estimating the performance of the accessory. The proposed INSGA-II modifies the crowded distance, crossover operator, and mutation operation to improve the population diversity and search capabilities of traditional NSGA-II. For comparison, a multiobjective optimization test of the rescue accessory is performed with the methods of INSGA-II, NSGA-II, PESAII, and SPEA2. Simulation results show that the Pareto front obtained by the proposed INSGA-II distributes more uniformly than those by the other algorithms, proving that INSGA-II has the highest effectiveness among all algorithms. These matters provide valuable design guides for designers. Especially, the compromise solutions of different algorithms are obtained and compared, and the comparison results show that the compromise solution of three objective functions obtained by INSGA-II is superior to those obtained by the other algorithms. This again proves that our designed novel rescue accessory has good performance compared with traditional ones.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the Special Project of Central Government Guiding Local Science and Technology Development (no. 2021L3029), the Leading Project of Fujian Province (no. 2020H0048), the Leading Technology Project of Sanming City (no. 2021-G-7), the National Natural Foundation Cultivation Project of Sanming University (no. PYT2006), and the Department of Education Science and Technology Program of Fujian Province (no. JAT200641).

References


proceedings of JSME annual conference on robotics and mechatronics, 2006.


