

# Research Status of RV Reducer as Key Component in Robotics

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## Abstract

**This paper systematically reviews the research status of RV reducers as key components in robotics, covering technical directions such as fault diagnosis, vibration analysis, and load-bearing performance optimization. A comprehensive technology matrix is constructed, and strategic development pathways for the industry are proposed. Benefiting from advantages including high precision, large torque capacity, and compact size, RV reducers are widely applied in fields such as robotics, CNC machine tools, and aerospace. The global market size grew from RMB 3.43 billion in 2018 to RMB 7.51 billion in 2023, with a Compound Annual Growth Rate (CAGR) of 16.97%. While domestic market share has exceeded 60%, the localization rate in high-end segments remains below 30%, constrained by bottlenecks such as reliance on imported critical processing equipment and incomplete design theory systems.**

## Keywords

**RV reducer; Fault detection; Bearing characteristics; Development status.**

## 1. Introduction

RV reducers, as core transmission components of industrial robots, possess advantages such as high precision, large torque, and small size, and are widely used in fields like robotics, CNC machine tools, aerospace, and more. The global market size expanded from 3.43 billion yuan in 2018 to 7.51 billion yuan in 2023, with a compound annual growth rate (CAGR) of 16.97%[1]. The domestic market share has surpassed 60%, yet the localization rate in high-end fields remains below 30%. There exist bottlenecks, including reliance on imports for key processing equipment and an imperfect design theory system[2]. The performance of RV reducers directly impacts the precision, lifespan, and reliability of robots, and technological breakthroughs in this area are crucial for enhancing the competitiveness of domestic robots. Current research primarily focuses on directions such as fault diagnosis, vibration analysis, load-bearing performance optimization, lightweight design, contact fatigue failure analysis, lifespan prediction, main bearing characteristics, intelligent operation and maintenance, accuracy degradation, and technological ecosystem. Fault diagnosis technology achieves a 92% accuracy rate in fault localization under variable speed conditions through SSA-VMD order tracking analysis[3]; vibration analysis technology reveals coupled vibration characteristics of multiple defects, with a 30% improvement in crankshaft vibration response; load-bearing performance optimization achieves an eccentricity influence coefficient of 0.0425 through a dynamic load-stress-stiffness model; lightweight design employs a BCC lattice structure combined with topology optimization, reducing the weight of the pin gear housing by 14.2% and the planet carrier by 28.9%; contact fatigue failure analysis reduces contact stress by 30% and increases contact ratio by 6% through tooth surface modification (drum shape + conical helical angle); lifespan prediction technology utilizes multi-domain degradation feature generation combined with a C-LSTM model, reducing prediction error by 81.2%; main bearing characteristic optimization enhances fatigue life by 54.6% through genetic algorithm parameter optimization

combined with full factorial verification; the intelligent operation and maintenance system facilitates multi-source data collection and predictive maintenance, improving diagnostic reliability through data fusion; the mechanism of accuracy degradation is investigated through a rolling bearing wear model combined with accelerated degradation testing, with a backlash increment accounting for 32.57%; the technological ecosystem promotes the synergy of precision reducers, controllers, and servo systems, with the localization rate surpassing 95%[4].

## 2. Overview of Current Technology Status

### 2.1. Fault localization method based on SSA-VMD order tracking analysis

This method optimizes the parameters of variational mode decomposition (VMD) through the Sparrow Search Algorithm (SSA), and combines order tracking analysis to achieve a 92% fault localization accuracy under varying speed conditions. The experiment was conducted on a swing fatigue test bench to verify the effectiveness of the method through low-order feature extraction. Compared with traditional methods, this approach demonstrates stronger robustness in noisy backgrounds. The specific experimental steps include: 1) preprocessing the collected time-domain vibration signals and speed signals; 2) optimizing the VMD parameters using SSA; 3) performing VMD decomposition on the equiangular domain vibration signals to obtain intrinsic mode functions (IMFs); 4) screening the IMFs using the kurtosis criterion; 5) applying MCKD processing to the target signal to enhance fault features; 6) performing envelope spectrum analysis to extract fault information. The experimental results show that this method clearly locates the fault points at low orders, achieving better fault diagnosis performance compared to traditional methods. This approach exhibits excellent performance under varying speed conditions and is suitable for complex conditions in actual industrial scenarios, with broad application prospects[5].

$$f(X) = \begin{bmatrix} f([x_{1,1} & x_{1,2} & \dots & x_{1,d}]) \\ f([x_{2,1} & x_{2,2} & \dots & x_{2,d}]) \\ \vdots \\ f([x_{3,1} & x_{3,2} & \dots & x_{3,d}]) \end{bmatrix} \quad (1)$$

In the formula,  $f$  represents the fitness of an individual. During each iteration, the position of the seeker will be updated to a new position, and its expression is as follows:

$$x_{i,j}^{t+1} = \begin{cases} x_{i,j}^t \exp\left(\frac{-i}{\beta \cdot T_{max}}\right), R_2 < f_{ST} \\ x_{i,j}^t + Q \cdot L, R_2 \geq f_{ST} \end{cases} \quad (2)$$

In the formula,  $x_{i,j}^{t+1}$  represents the position information of the  $i$ th sparrow in the  $j$ th dimension;  $T_{max}$  denotes the maximum number of iterations;  $\beta$  is a random number;  $R_2$  stands for the alarm value,  $f_{ST}$  is the safety threshold,  $Q$  is a random number from a normal distribution; and  $L$  is a matrix where each internal element is 1.

The initial position of the forecaster is randomly generated within the population, and its mathematical model is

$$x_{i,j}^{t+1} = \begin{cases} x_{best}^t + \beta \cdot |x_{i,j}^t - x_{best}^t|, f_i \neq f_g \\ x_{i,j}^t + M \cdot \left[ \frac{|x_{i,j}^t - x_{worst}^t|}{(f_i - f_w) + \varepsilon} \right], f_i = f_g \end{cases} \quad (3)$$

In the formula,  $x_{best}^t$  represents the current global optimal position; M is a random number within the range of  $[-1, 1]$ , indicating the direction of sparrow movement;  $f_i$  denotes the current fitness of the sparrow;  $f_g$  and  $f_w$  represent the current global optimal and worst fitnesses, respectively;  $\varepsilon$  is an intermediate variable. If  $f_i > f_g$ , it indicates that the sparrow is at the edge of the flock; if  $f_i = f_g$ , it signifies that the sparrow has sensed danger within the flock and needs to get closer to other sparrows to reduce risk.

## 2.2. Multi-domain degenerate feature generation and fusion with C-LSTM model

By generating virtual samples with TimeGAN to expand the training dataset, and combining a hybrid model of CNN and LSTM to establish a mapping relationship between degradation features and remaining lifespan, the experimental results show a significant improvement in lifespan prediction accuracy, with a prediction error reduction of 81.2% (RMSE). The specific implementation steps include: 1) Extracting initial features from multiple information domains in vibration signals and constructing a performance degradation indicator system; 2) Using TimeGAN to generate virtual samples with a distribution similar to real degradation feature data, thereby expanding the training dataset; 3) Designing a C-LSTM model that integrates CNN and LSTM, combining CNN's spatial feature extraction capability and LSTM's time series modeling capability to enhance lifespan prediction accuracy. The experimental results demonstrate that this method excels in both data generation quality and lifespan prediction accuracy, indicating high application value. This method innovates in generating degradation features from multiple domains, providing a new perspective for lifespan prediction of RV reducers. Additionally, the signal undergoes empirical mode decomposition, yielding multiple intrinsic mode functions (IMFs) arranged in descending order of frequency. The instantaneous energy of the first six IMFs is calculated to obtain features F27-F32, with the calculation formula as follows:

$$E_l = \sum_{n=1}^N (n \cdot \Delta t) (c_l(n \cdot \Delta t))^2 \quad (4)$$

In the formula,  $\Delta t$  represents the sampling interval, and  $c_l$  denotes the l-th intrinsic mode component obtained through decomposition. Subsequently, the normalized instantaneous energy of each component is calculated as:  $F_{33+1} = E_l / \sum_{l=1}^6 E_l$ , where  $E_l$  is the instantaneous energy of the l-th component.

F39 and F40 represent two new standard deviation metrics: one is the standard deviation of the inverse hyperbolic sine transformation values (SDof IHS), and the other is the standard deviation of the inverse tangent transformation values (SD of IT). Their calculation formulas are as follows:

$$\begin{cases} SD \text{ of IHS} = \sigma(\log(V_n + \sqrt{V_n^2 + 1})) \\ SD \text{ of IT} = \sigma\left(\frac{i}{2} \log\left(\frac{i+V_n}{i-V_n}\right)\right) \end{cases} \quad (5)$$

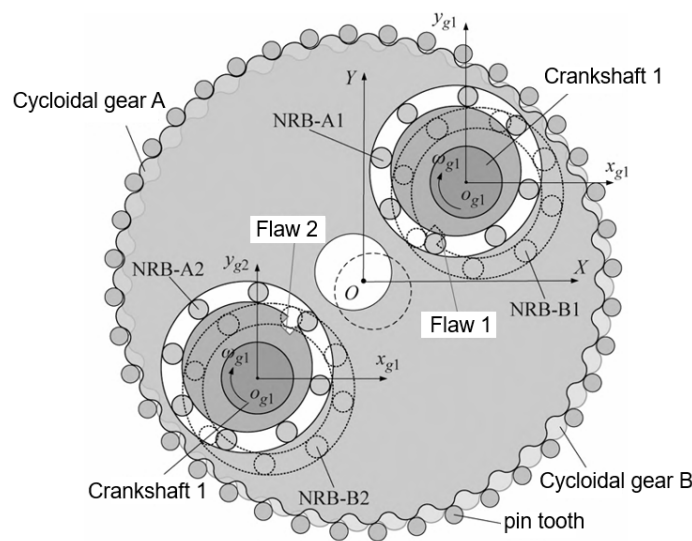
A feature sensitive to the degradation process of an RV reducer should exhibit a monotonic degradation trend. To measure the monotonic trend of each feature, a trend index is selected for evaluation. The trend of the feature is represented by calculating the Spearman correlation coefficient between the feature and time:

$$\rho^k = \frac{|\sum_{l=1}^L (T_l - \bar{T}_l)(Y_1^k - \bar{Y}_1^k)|}{\sqrt{\sum_{l=1}^L (T_l - \bar{T}_l)^2 \sum_{l=1}^L (Y_1^k - \bar{Y}_1^k)^2}} \tag{6}$$

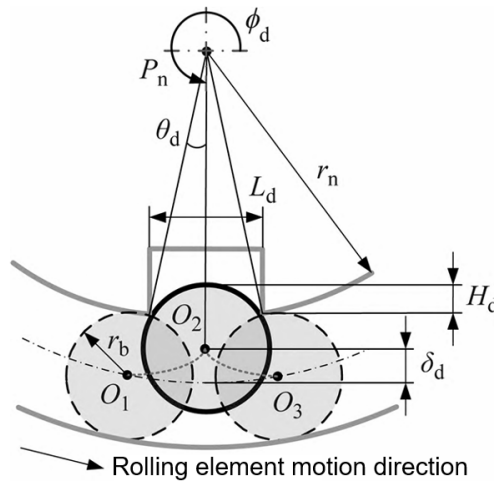
In the formula,  $\{T_l\}_{l=1:L}$  represents the sequence of data acquisition time points for the RV reducer throughout the entire working cycle, while  $\{T_l^k\}_{l=1:L}$  ( $k = 1, 2, \dots, 40$ ) corresponds to the initial feature set consisting of 40 original features mentioned in the previous section. Here,  $L$  represents the total number of times data acquisition is completed throughout the entire process of performance degradation, and  $\bar{T}_l$  and  $\bar{Y}_1^k$  correspond to the mean parameters of each sequence, respectively. For each feature, if its value exhibits a clear monotonic increasing or decreasing trend over time, a trend index of 1 is assigned; if the value remains stable or exhibits irregular fluctuations, the index is recorded as 0. It can be inferred that a higher trend index value indicates a stronger monotonicity of the feature over time.

### 2.3. Vibration analysis technology

By establishing a dynamic model of an RV reducer with multiple sets of needle roller bearing defects, the vibration response characteristics under different defect combination patterns were analyzed. Experimental results showed that bearing defects had a significant impact on the vibration characteristics of the crankshaft and output planet carrier, while having a relatively minor effect on the vibration characteristics of the cycloid gear. Frequency domain analysis indicated the presence of modulation phenomena near each characteristic frequency, caused by the rotational frequencies of the crankshaft and cycloid gear. This method is innovative in the analysis of coupled vibration characteristics of multiple defects, providing a new perspective for the study of vibration characteristics of RV reducers [6].



**Figure 1.** Schematic diagram of multi-mode defects in needle roller bearings



**Figure 2.** Schematic diagram of the rolling element passing through the defect

As shown in Figure 2, the motion trajectory of the rolling element as it passes through the defect is  $O_1 \rightarrow O_2 \rightarrow O_3$ , and the maximum value  $H_d$  of the time-varying displacement  $\delta_{d,j}$  can be solved using Equation (7)

$$H_d = r_b - \sqrt{(r_b)^2 - \left(\frac{L_d}{2}\right)^2} \tag{7}$$

In the formula:  $r_b$  represents the radius of the rolling element;  $L_d$  denotes the width of the defect.

The time-varying displacement  $\delta_{d,j}$  can be represented by  $H_d$ :

$$\delta_{d,j} = \begin{cases} H_d \cos \left\{ \frac{\pi [\text{mod}(\beta_{b,j}, 2\pi) - \text{mod}(\phi_d, 2\pi)]}{2\theta_d} \right\}, & \text{mod}(\phi_d, 2\pi) - \theta_d \leq \text{mod}(\beta_{b,j}, 2\pi) < \text{mod}(\phi_d, 2\pi) \\ H_d, & \text{mod}(\beta_{b,j}, 2\pi) = \text{mod}(\phi_d, 2\pi) \\ H_d \cos \left\{ \frac{\pi [\text{mod}(\beta_{b,j}, 2\pi) - \text{mod}(\phi_d, 2\pi)]}{2\theta_d} \right\}, & \text{mod}(\phi_d, 2\pi) < \text{mod}(\beta_{b,j}, 2\pi) \leq \text{mod}(\phi_d, 2\pi) + \theta_d \\ 0 & \text{other} \end{cases} \tag{8}$$

In the formula,  $\phi_d$  represents the central position angle of the defect;  $\text{mod}$  denotes the modulo operation; other indicates that the rolling element has not passed through the defect area;  $\theta_d$  signifies the span angle between the defect edge and the defect center, which can be calculated using formula (9).

$$\theta_d = \arcsin \left( \frac{L_d}{2r_n} \right) \tag{9}$$

In the formula,  $r_n$  represents the radius of the bearing inner raceway. When the rolling element passes through the defect area, the total contact deformation is(10).

$$\delta_{b,j} = e_{x1} \cos \beta_{b,j} + e_{y1} \sin \beta_{b,j} - \delta_{d,j} \tag{10}$$

By establishing a dynamic load stress stiffness model, the influence of eccentricity on load-bearing performance was analyzed. Experimental results showed that the eccentricity influence coefficient was 0.0425, and the finite element simulation error was less than 5%. This method is innovative in load-bearing performance optimization and provides new ideas for improving the load-bearing performance of RV reducers [7]. By adopting a BCC lattice structure combined with topology optimization, a weight reduction of 14.2% for the pin gear housing and 28.9% for the planet carrier was achieved. Static analysis combined with SLM printing verification demonstrated that this method is innovative in lightweight design and provides new ideas for lightweight design of RV reducers [8]. Through tooth surface modification (drum shape + conical helical angle), the contact stress was reduced by 30%, and the contact ratio was increased by 6%. MASTA simulation combined with durability testing verification showed that this method is innovative in contact fatigue failure analysis and provides new ideas for contact fatigue failure analysis of RV reducers [9]. Through multi-domain degradation feature generation combined with a C-LSTM model, the error in lifespan prediction was reduced by 81.2% (RMSE). TimeGAN data generation combined with accelerated lifespan testing verification demonstrated that this method is innovative in lifespan prediction and provides new ideas for lifespan prediction of RV reducers [10].

### 3. Industrial Ecology Analysis

The RV reducer industry chain encompasses upstream raw material and core component supply, midstream design, production, and testing, as well as downstream application fields. The upstream involves raw materials such as steel and bearing steel, along with core components like gears and bearings. The midstream includes design, processing, assembly, and testing. The downstream finds applications in fields like robotics, CNC machine tools, new energy vehicles, aerospace, and more. Specific examples include: 1) Zhuhai Feima's practice in RV reducer design and production, where advanced equipment and technology were introduced to enhance production efficiency and product quality; 2) Julun Intelligent's innovation in the testing phase, where a high-precision testing platform was developed to improve testing efficiency and accuracy; 3) Zhejiang Shuanghuan Transmission's breakthrough in domestic substitution, where independent research and technological innovation enabled the localization of high-end RV reducers. The coordinated development of all links in the industry chain drives the overall progress of the RV reducer industry [11,12].

The global market is highly concentrated, with Japan's Nabtesco accounting for approximately 60% of the global market share, forming a long-term technological monopoly. Domestic brands have achieved a domestic market share exceeding 60% for the first time, forming a pattern of "one superpower and multiple strong players". Domestic RV reducers still lag behind international advanced levels in key aspects such as materials and precision control. However, policy promotion, capacity expansion, and the outbreak of downstream demand have accelerated the process of domestic substitution. Domestic substitution is moving from the mid-to-low end to the high end, and has formed technological output capabilities in emerging fields such as humanoid robots and aerospace [13].

National and local governments have introduced relevant policies to support the core technology research, promotion, and application of RV reducers, driving high-quality industrial development. The National Key Laboratory for High-end Heavy-load Robots' open research projects and Guangdong Provincial Science and Technology Plan projects support the development of the RV reducer industry. Policy support includes establishing a theoretical foundation for the forward design of reducers, focusing efforts on tackling major processing equipment, constructing a collaborative innovation system across the upstream and downstream of the industrial chain, strengthening the construction of testing and inspection

capabilities, and promoting the integrated application of artificial intelligence technology and industry.

Domestic RV reducers face deficiencies in key processing equipment, such as high-precision grinding centers and gear machining centers, which rely on imports, affecting production efficiency and product quality. It is necessary to focus on overcoming major processing equipment and enhancing the security and resilience of the industrial and supply chains. Specific measures include: 1) increasing R&D investment to break through key equipment such as high-precision grinding centers; 2) promoting industry-university-research cooperation to accelerate technology transformation; 3) introducing advanced foreign technology, digesting, absorbing, and innovating. Through these measures, we will gradually achieve the localization of key processing equipment and enhance the self-control ability of the industrial chain [14].

Domestic RV reducers exhibit deficiencies in design simulation and heat treatment process capabilities, which affect their precision retention. It is necessary to strengthen the construction of design simulation and heat treatment process capabilities to enhance precision retention. Specific measures include: 1) strengthening the construction of design simulation capabilities to improve design precision; 2) strengthening the construction of heat treatment process capabilities to enhance heat treatment quality; 3) promoting industry-university-research cooperation to accelerate technology transformation.

The insufficient collaboration between upstream and downstream enterprises in the industrial chain affects the overall competitiveness of the industrial chain. It is necessary to strengthen cooperation and collaboration between upstream and downstream enterprises in the industrial chain to enhance the overall competitiveness of the industrial chain. Specific measures include: 1) strengthening cooperation and collaboration between upstream and downstream enterprises in the industrial chain; 2) promoting information sharing between upstream and downstream enterprises in the industrial chain; 3) promoting technological cooperation between upstream and downstream enterprises in the industrial chain.

By applying new composite materials, such as carbon fiber reinforced composites and ceramic matrix composites, the load-bearing capacity and service life of RV reducers are enhanced. These new materials possess advantages such as high strength, high wear resistance, and low density, which can significantly improve the performance of the reducers. Specific application cases include: 1) the application of carbon fiber reinforced composites in the housing of RV reducers to enhance the strength and lightweight of the housing; 2) the practice of ceramic matrix composites in gear components to improve the wear resistance and service life of gears; 3) experimental data on the use of new materials to enhance the service life of reducers, verifying the performance advantages of the materials [15].

The full lifecycle health management of RV reducers is achieved through digital twin technology. Digital twin technology enables real-time monitoring of the operating status, fault prediction, health management, and other functions of the reducers, thereby enhancing their operational reliability and lifespan. Specific application cases include: 1) the application of digital twin technology in the health management of RV reducers; 2) the application of digital twin technology in the fault prediction of RV reducers; 3) the application of digital twin technology in the full lifecycle management of RV reducers [16].

By utilizing new processing technologies such as laser cladding and electron beam welding, the processing quality and efficiency of RV reducers can be enhanced. These novel processing techniques boast advantages like high precision, high efficiency, and low energy consumption, which can significantly improve the processing quality and efficiency of reducers. Specific application cases include: 1) the application of laser cladding technology in the gear processing of RV reducers; 2) the application of electron beam welding technology in the housing

processing of RV reducers; 3) experimental data demonstrating the improvement in processing quality and efficiency of reducers achieved by new processing technologies.

#### 4. Countermeasures and Suggestions

Leading enterprises are encouraged to strengthen theoretical and technological research, and form a comprehensive RV reducer design system. By establishing forward design theory, design efficiency and product quality can be improved, supporting the breakthrough of domestic RV reducers in high-end fields [17]. Specific measures include: 1) establishing a forward design theoretical framework to clarify design processes and standards; 2) tackling key technical challenges to solve technical problems in design; 3) promoting the formulation of design standards to standardize design processes and results.

Focus on developing major processing equipment, such as high-precision grinding centers and gear machining centers, to enhance the security and resilience of the industrial and supply chains. Specific measures include: 1) increasing R&D investment to make breakthroughs in key equipment; 2) promoting industry-university-research cooperation to accelerate technology transfer; 3) introducing advanced foreign technology, assimilating it, and then innovating upon it.

Promote the integrated application of artificial intelligence technology and industry to achieve "overtaking on the curve" in the design, manufacturing, and quality control capabilities of domestic RV reducers. Specific measures include: 1) strengthening the research and development of artificial intelligence technology to enhance its technical level; 2) promoting the application of artificial intelligence technology in the design, manufacturing, and quality control of RV reducers; 3) strengthening the cultivation of artificial intelligence technology talents to improve the application capabilities of artificial intelligence technology.

#### 5. Summary

This article systematically reviews the current research status of RV reducers, constructs a comprehensive matrix of the technology system, and proposes strategic paths for industrial development. In the future, it is necessary to break through key processing equipment, establish a forward design theoretical system, promote the integration of artificial intelligence technology, and achieve full-chain autonomy and controllability. With continuous technological advancements, RV reducers will play a more important role in fields such as robotics and aerospace. Specific prospects include: 1) precision development direction to enhance the performance and lifespan of the reducers; 2) intelligent technology integration to achieve full-lifecycle health management; 3) material and process innovation to promote performance improvement and cost reduction of the reducers. Through these measures, we will gradually achieve full-chain autonomy and controllability of RV reducers, supporting the high-quality development of the domestic robotics industry.

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