Innovative Design of Intelligent Sorting Robot Based on TRIZ Theory

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Abstract: Traditional sorting robots suffer bulky frames, limited workspace, poor human -robot collaboration safety and low integration. This paper adopts TRIZ theory to complete a full innovative design of intelligent sorting robots. The Nine-Screen Method, three-axis problem analysis and functional modeling identify core system defects. Two groups of technical contradictions are resolved via TRIZ contradiction matrix and corresponding inventive principles. Substance-field models, 76 standard solutions and the Little People Method address physical contradictions between robotic performance, equipment complexity and manufacturing cost. Spatial, sensing and multi-physical field extended resources are fully exploited to integrate multiple separation principles. All candidate schemes are evaluated for practicality. The optimal six-degree-of-freedom collaborative robot adopts integrated drive-control joints, composite lightweight links and binocular vision sensing. It eliminates fixed safety fences and realizes barrier-free human-machine sorting. This work provides standardized design references for compact, high-performance collaborative sorting robotic platforms.

Keywords: TRIZ Theory; Sorting Robot; Functional Analysis; Technical Contradiction; Physical Contradiction

1. Introduction

Innovation methodologies integrate scientific thinking, analytical approaches and practical tools, serving as the foundation of independent technological innovation. TRIZ (Theory of Inventive Problem Solving), recognized as a world-class innovation system, uncovers inherent laws of invention and design. Unlike trial-and-error development or compromise-based optimization, TRIZ analyzes full product lifecycles following technical evolution patterns [1]. Modern TRIZ covers systematic innovative thinking, laws of technical system evolution, forty inventive principles, thirty-nine general engineering parameters for technical contradiction resolution, physical contradiction solving, substance-field modeling and seventy-six standard solutions [2].

Manual sorting dominates traditional production lines. Rising industrial automation speeds up manufacturing rhythms and raises workload intensity. Human vision cannot meet high-throughput requirements, so robotic sorting equipment replaces manual labor across most production segments [3].

Against the backdrop of Made in China 2025 and Industry 4.0, automatic sorting equipment becomes mainstream industrial hardware. Applying TRIZ to robotic design drastically shortens development cycles, boosts production throughput and accelerates full automation of sorting workflows [4].

This study converts practical industrial challenges into standardized TRIZ problem models. Sequential TRIZ analytical tools generate universal solution models, which guide the conceptual design of next-generation intelligent sorting robots [5].

2. Functional Analysis of Sorting Robots

The nine-screen method is a core systemic thinking tool within TRIZ. It evaluates the target system alongside its subsystems and supersystems while accounting for past, present and future developmental states [6]. Time axes track historical evolution and future trends. Spatial axes distinguish the core system, its internal sub-components and external super-system environment [7]. The method identifies available resources by examining each dimension’s historical and prospective states to trace root causes and derive feasible solutions, as illustrated in Figure 1.

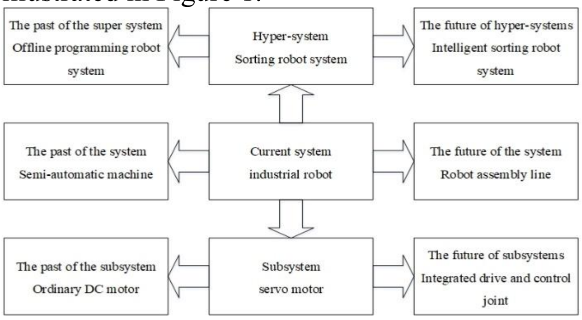


Figure 1. Nine-Screen Method for Robotic Systems

The core system analyzed herein refers to traditional industrial robots. Key drawbacks include oversized structures, high procurement costs and insufficient human-machine collaboration safety.

Figure 1 shows semi-automatic machinery as the historical predecessor of industrial robots, and ordinary DC motors as early subsystem drive components. Robots function as labor-replacing equipment. Conventional industrial robots cannot adapt to modern digital workshops due to large size and poor collaborative safety. Servo motors replace DC motors to minimize overall equipment volume, featuring compact structures, high rotational speed and high positioning accuracy [8].

Servo motors deliver closed-loop control over position, velocity and torque to eliminate stepping motor out-of-step faults [9]. Their rated speed ranges from 2000 to 3000 rpm with stable high-speed operation. Servos sustain three times rated torque without damage, suiting rapid startup and fluctuating load scenarios. Low-speed rotation remains smooth without stepping vibration [10]. Dynamic acceleration and deceleration complete within tens of milliseconds [11]. Heat generation and noise are significantly lower than competing motor types. The primary drawback of servo hardware lies in its high upfront cost. Costs will gradually decline as collaborative automation gains popularity, making servo actuation mainstream.

Nine-screen analysis summarizes three critical flaws of conventional industrial robots: excessive overall mass, fixed installation positions and lack of collaborative safety. Table 1 documents structural characteristics of super-systems, core systems and subsystems, alongside their historical and future iterations.

Drawing upon the descriptions of functional problems pertaining to robot system components presented in Table 1, a range of solutions along with their respective characteristics have been delineated for the diverse issues identified. Through meticulous analysis and elemental expansion of the existing system, its subsystems, and supersystems, an analytical breakdown of the functional components within the robot system has been achieved, as illustrated in Figure 2.

Table 1. Description of the Functional Problem of the Robot System Components

Current problem description: Industrial robots have issues such as large size, fixed position, and lack of collaborative safety		
System Name	System Category	Features & Deficiencies
Current technical system	Industrial robot	Large volume; fixed position; lacking in
System past	Semi-automatic machine	Real-time remote control
System future	Robot assembly line	System complexity
Subsystem	Servo motor	Low load
Supersystem	Sorting robot system	Small size; good portability; secure collaboration
The past of the subsystem	Ordinary DC motor	Low accuracy and poor adaptability
The future of subsystems	Integrated drive and control joint	Compact structure; well-integrated; high power density
The past of the supersystem	Offline programming robot system	Offline programming, repetitive work
The future of supersystem	Intelligent sorting robot system	Intelligent sorting work, unmanned factory

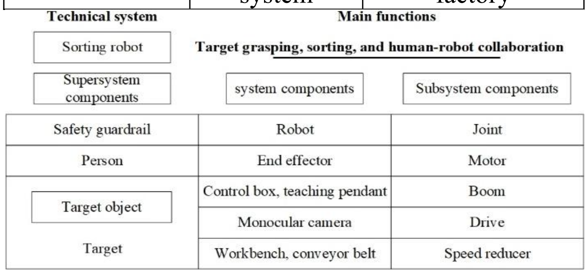


Figure 2. Robot System Functional Components

Drawing on the content delineated in Table 1 and Figure 2, we constructed a component relationship matrix for the robot system, which includes components from individual elements, subsystems, and the super-system of the robot system, as depicted in Figure 3.

Matrix analysis reveals five critical limitations of conventional industrial robots: ①Cumbersome external wiring restricts robot workspace and achievable postures; ②Heavy, bulky structures limit mobility and reconfiguration; ③Large inertial mass requires fixed safety fences to separate operators from equipment; ④Disassembling and replacing end effectors proves inefficient due to tangled wiring and oversized tooling; ⑤Oversized control cabinets occupy valuable floor space, consume excess power and generate loud operating noise, hindering human-machine interaction.

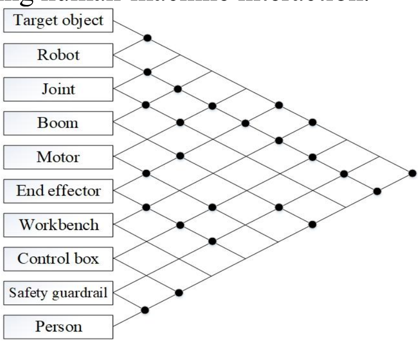


Figure 3. Component Relationship Matrix Analysis Diagram of Robot System

Inter-component functional relationships are classified into sufficient, insufficient, excessive and harmful interactions (Figure 4).

Drawing upon the results presented in Table 1, Figure 2, Figure 3, and Figure 4 of the robot system, a functional analysis is conducted by dissociating the components from their respective functions. These functions are subsequently classified into main functions, basic functions, and auxiliary functions based on their hierarchical levels.

① Primary functions: Core system objectives realized by the overall robotic platform;

② Basic functions: Indispensable component actions that complete primary sorting tasks;

③ Auxiliary functions: Supporting behaviors that guarantee normal basic function execution [12].

Functions can be classified based on their relationship with the primary function as follows:

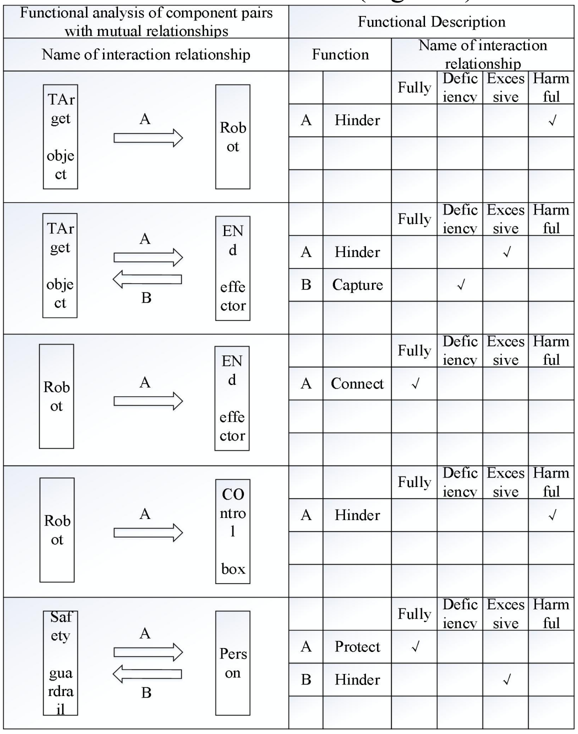
① Useful function: fully, deficiency, excessive

② Harmful function

③ Neutral function

Figure 5 displays the complete functional model of the original robotic system, marking normal, insufficient, excessive and harmful interactions via standardized line notation.

TRIZ functional trimming rules permit removing neutral and auxiliary functions that impose unnecessary constraints without disrupting primary tasks. Components can be trimmed if other hardware fulfills their core functions [13]. Safety fences, separate motors and discrete joints are removed from the original model to generate the trimmed functional model (Figure 6).



Functional analysis of component pairs with mutual relationships: Name of interaction relationship	Functional Description: Function		Name of interaction relationship: Fully	Deficiency	Excessive	Harmful
TArget object —A→ Robot	A	Hinder				√
TArget object —A→ ENd effector; ←B—	A	Hinder			√	
	B	Capture		√		
Robot —A→ ENd effector	A	Connect	√			
Robot —A→ COntrol box	A	Hinder				√
Safety guardrail —A→ Person; ←B—	A	Protect	√			
	B	Hinder			√	

Figure 4. Robotic Systems Exist in Relation to Component Function Analysis

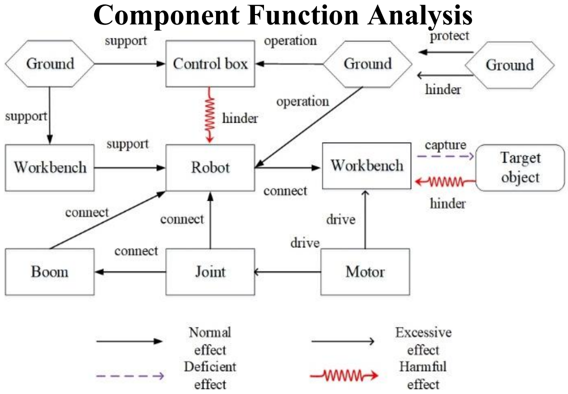


Figure 5. Component Functional Model Diagram of the Robot System

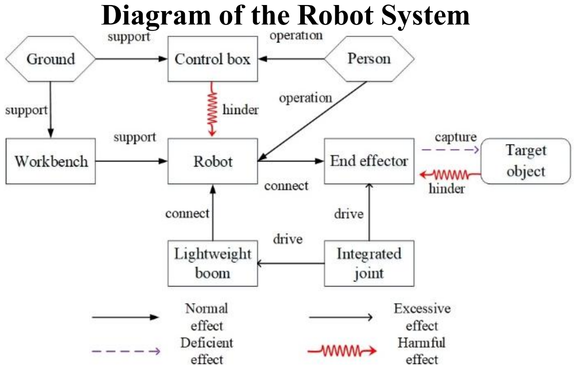


Figure 6. Cropped Functional Model Diagram

Replacing discrete motor-joint assemblies with integrated drive joints paired with lightweight arm segments eliminates mandatory safety barriers and improves human-machine interactivity.

3. Technical Contradiction Analysis and Resolution

To uncover the genuine issues concealed beneath superficial problems, pinpoint the entry points for resolving them, and dissect the systemic resources necessary for problem-solving, thereby minimizing the expenditure associated with problem resolution, the three-axis problem analysis method can be utilized. As depicted in Figure 7, the initial problem is analyzed and delineated along the process timeline axis (operation axis), system hierarchy axis (system axis), and causal relationship axis (causal axis), breaking down intricate engineering problems into several sub-problems. Operation axes clarify sequential process links. System axes identify exploitable resources to lower redesign costs.

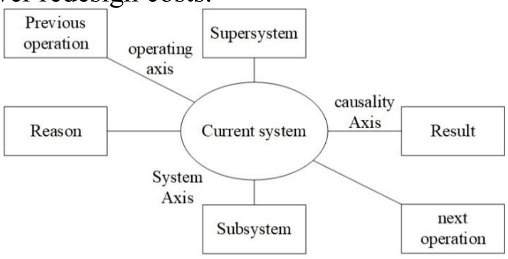


Figure 7. Three-Axis Problem Analysis Method

Causal axis analysis, also known as causal chain analysis, identifies the root triggers of failures by mapping logical chains linking causes and corresponding outcomes, with the core objective of tracing fundamental sources of system defects [14]. This study establishes a causal axis model for the robotic sorting system (Figure 8) to dissect deep-seated latent flaws within the technical system and clarify logical correlations between surface-level malfunctions and underlying root defects. Combined with component functional modeling, four core problematic bottlenecks are extracted:

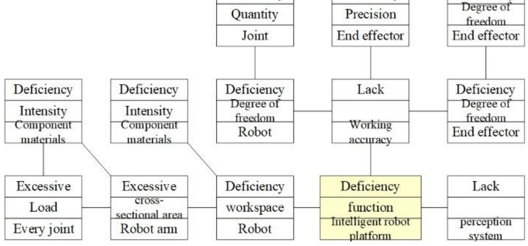


Figure 8. Causal Axis Analysis for Robotic Systems

Key points①: Limited degrees of freedom and constrained working envelopes narrow the robot's functional range and restrict its applicable scenarios.

Key points②: Restricted end-effector pose adjustment limits the types of target objects the robot can grasp.

Key points③: Closed-source architecture and scarce development interfaces constrain the robot's expandable functionality.

Key points④: Insufficient human-machine interaction sensors degrade operational safety and fail to meet collaborative work requirements.

The problem space is first narrowed to derive localized improvement paths. This strategy avoids introducing extra external resources to prevent rising system complexity, enabling elimination of harmful functions and realization of useful functions through minimal structural modifications. For Bottleneck ①, the narrowed problem statement reads: Integrate new internal system resources to adopt modular joint structures and increase joint quantity, reduce external wiring, expand motion freedom and working space, boost positioning accuracy, and enrich overall robotic functionality.

From another perspective, the scope of problem-solving cannot be limited. By "expanding the problem", the options for change are no longer restricted, and other factors do not need to be considered, which is conducive to discovering new ways to solve the problem. At this time, the method of "expanding the problem" is used to search for alternative problem descriptions [15], as shown in Table 2.

Analysis of Table 2 confirms that optimizing low degrees of freedom and wiring interference generates inherent system conflicts while expanding robotic functionality, which manifests as technical contradictions.

Technical Contradiction (TC1)	IF Use integrated joints, increase the number, and optimize internal wiring (C+)	Use integrated joints, increase the number, and improve internal wiring	The robot's working space is expanded and its functions are improved
	THEN The robot's working space has been expanded and its functions have been improved (A1)		
	BUT Cost increases, and the operability and complexity of equipment deteriorate (B1)		Cost increases, and the operability and complexity of equipment deteriorate
Technical Contradiction (TC2)	IF Joints are not integrated, reduced in number, and external wiring is minimized (C-)	The joints are not integrated, the number is reduced, and external wiring is minimized	Cost reduction, improved operability, and reduced equipment complexity
	THEN Cost reduction, improved operability, and reduced equipment complexity (A2)		
	BUT The robot's working space is reduced and its functionality deteriorates (B2)		The robot's working space is reduced and its functionality deteriorates
TC choice	Choosing how to enhance useful functions rather than how to reduce harmful ones	Select TC1	

Figure 9. Define Two Technical Contradictions

Table 2. "Expanding the Problem" to Find a Description of the Alternative Problem

Analysis Dimension		Is It Possible	Alternative Problem Statement
System Composition	Supersystem	Can	Integrated drive and control joint
	Subsystem	Can	Increase joint count and raise joint reduction ratios
Time	Past	——	——
	Future	Can	
Causality	Reason	Can	The routing of wires affects the range of motion
	Result	Can	Increasing joints, internal wiring, and additional functions lead to rising costs
Input-Output	Input	——	——
	Output	——	——

Technical contradictions refer to incompatible performance demands within a single system: optimizing one system parameter inevitably degrades another. Two distinct technical contradictions (TC1, TC2) are defined and visualized in Figure 9. The unified contradiction description is as follows: Drive-control integrated joints, additional joint units and internal wiring are implemented to improve system adaptability and versatility, yet these modifications increase hardware costs and worsen system operability and structural complexity.

Genrich Altshuller and his research team summarized 39 universal engineering parameters by analyzing massive patent documents, which standardize performance indicators for technical systems and translate practical technical conflicts into standardized TRIZ contradictions [16]. Cross-referencing the contradiction matrix yields the following inventive principles for the two groups of conflicting parameters [17]:

(1) Improved parameter: Adaptability or versatility; Worsened parameter: Ease of operation.

①Principle 15: Dynamism;

②Principle 34: Discard and recover;

③Principle 1: Segmentation;

④Principle 16: Partial or excessive action.

(2) Improved parameter: Adaptability or versatility; Worsened parameter: Complexity of device.

①Principle 15: Dynamism;

②Principle 29: Pneumatic and hydraulic constructions;

③Principle 37: Thermal expansion;

④Principle 28: Mechanics substitution.

Twelve targeted technical solutions are derived from the above inventive principles:

Solution 1 (Principle 15: Dynamism)

The dynamism principle advocates flexible structural design to enhance environmental adaptability, replaces reciprocating motion with rotary mechanisms, endows single components with multi-purpose functions, and optimizes component flexibility to accommodate diverse operating environments.

This solution deploys drive-control integrated joints to replace conventional discrete motors and reducers, increases joint quantity, and assembles six integrated joints in series with connecting linkages to construct a 6-degree-of-freedom serial robotic arm. Joint load ratings and protection grades are customized according to on-site working conditions to satisfy multi-stage operational demands and substantially expand system functionality.

Solution 2 (Principle 34: Discard and recover)

Time sequence governs the discard-and-recover principle: components serving temporary functions are detached once their tasks conclude, or restored for repeated utilization.

Built upon Solution 1, this design installs a standardized quick-disconnect flange and universal communication ports at the robot end. The unified flange structure supports rapid swapping of end-effectors, including electric two -finger grippers, pneumatic clamps and vacuum suction cups via bolted connections, greatly broadening the robot's grasping compatibility.

Solution 3 (Principle 1: Segmentation)

The segmentation principle requires decomposing problematic physical or conceptual system modules for separate reconfiguration and combination [18].

Based on Solution 2, the complete robotic system is split into independent modular units: serial manipulator body, interchangeable end-effectors, dedicated controllers and teaching pendants. Plug-in slots and detachable cables enable convenient assembly, disassembly and iterative system reconstruction to upgrade functional performance.

Solution 4 (Principle 16: Partial or excessive action)

When optimal system performance cannot be directly achieved, this principle guides iterative testing of under- and over-sized structural configurations to balance performance tradeoffs.

Extending Solution 1, a 7-degree-of-freedom anthropomorphic serial arm assembled with seven independent integrated joints avoids singular motion points inherent to 6-degree-of-freedom manipulators and delivers richer motion trajectories. However, this design raises manufacturing costs, reduces end payload capacity and complicates kinematic algorithms. A 6-degree-of-freedom configuration delivers sufficient performance under non-singular motion conditions while maintaining cost efficiency.

Solution 5 (Principle 29: Pneumatic and hydraulic constructions)

This principle leverages the compressible or incompressible properties of fluid media to substitute rigid mechanical structures [19].

Building on Solution 2, soft vacuum suction cups replace rigid electric two-finger grippers and mount to the standardized end flange. Paired with air compressors, the vacuum system achieves simple, reliable adsorption of irregular target workpieces and expands functional applicability.

Solution 6 (Principle 37: Thermal expansion)

Thermal expansion and contraction respond to multiple environmental stimuli including temperature, gravity, altitude, air pressure and light intensity, rather than only thermal fields [20].

Derived from Solution 1, drive-control integrated joints are fully encapsulated inside the manipulator frame, blocking real-time internal temperature observation. Bimetallic thermal switches are installed on main circuit branches; dissimilar thermal expansion coefficients bend the dual metal sheets under overheating to trigger circuit cutoffs and improve overall operational safety.

Solution 7 (Principle 28: Mechanics substitution)

This principle replaces rigid mechanical interactions with optical, acoustic or variable physical fields, and substitutes mechanical conceptual frameworks with alternative abstract models.

Integrating Solutions 1 through 6, optical intelligent vision sensors and acoustic voice control modules replace single mechanical actuation frameworks, upgrading the 6-degree-of-freedom serial manipulator into a multi-functional flexible collaborative robotic platform with comprehensive functional coverage.

4. Physical Contradiction Analysis and Resolution

Most system conflicts manifest as technical contradictions solvable via the TRIZ contradiction matrix. Physical contradictions emerge when a single parameter requires mutually exclusive optimization directions within one technical system, representing a core TRIZ conflict category [21]. Figure 10 illustrates the standardized workflow for physical contradiction definition.

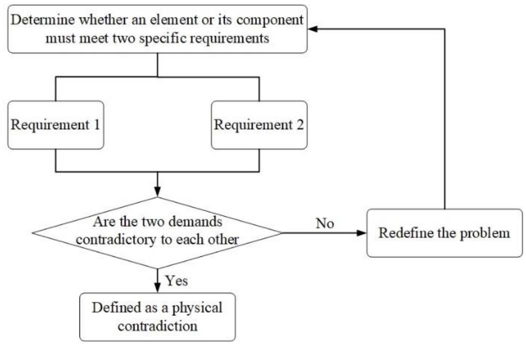


Figure 10. Flowchart for Defining Physical Contradiction

Physical contradictions embody the unity of opposites in dialectical materialism, where conflicting elements within a technical system rely on each other while exerting opposing effects. The component carrying conflicting dual attributes is defined as the key element, which may refer to subsystems, material properties, substances or physical fields. Accurate characterization of physical contradictions directly determines the effectiveness of subsequent optimization, as summarized in Table 3.

Table 3. Description of Physical Contradiction Problems

Searching for X1 of physical contradiction		
Route 1	Fully useful leads to harmful reinforcement	The integration of drive and control into a single joint leads to increased costs, deteriorated operability, and greater equipment complexity.
Route 2	Eliminate harmful effects, but weaken useful ones	Traditional forms lead to deterioration in robot performance and functionality.
Intensify conflict	——	Operability and equipment complexity cannot be achieved.
Problem descripti	——	It is necessary to find X1 and X2 to improve the

on		performance of the robotic arm, while not affecting its operability and equipment complexity.

To identify the target variable X_1, substance-field modeling—a core analytical tool within TRIZ—is introduced [22]. The substance-field analysis method establishes functional models for existing technical systems, as every engineered system is constructed to fulfill specific functional requirements.

The ultimate function this method aims to achieve is that the output of an object or substance is caused by the action of another object (tool) or certain fields (types of energy) [23]. According to the requirements of the actual problem, a substance-field model is constructed as shown in Figure 11.

The core logic of substance-field modeling states that functional output from a substance occurs when a secondary substance (tool) or energy field imposes interactive effects upon it. Interactions describe the functional outcomes generated by couplings between substances and fields; technical systems exist solely to deliver targeted functions, making functional analysis central to value engineering. Substance-field models fall into four primary classifications. Designers prioritize fully functional, complete substance-field models, while incomplete, insufficient-effect, and harmful-effect models fail to meet system functional demands. TRIZ provides six generic solution routes and 76 standard inventive solutions to resolve defective substance-field configurations.

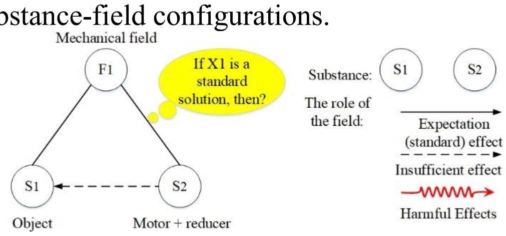


Figure 11. Object-Field Model Diagram

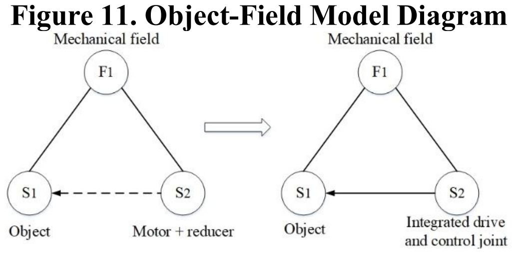


Figure 12. Diagram of the Improved Object-Field Model

After constructing the substance-field model corresponding to the robotic design conflict, the 76 standard solutions are deployed from the X_1 optimization perspective. The applicable solution derived is Level 2 Standard Solution S2.2.4: Enhance system flexibility and adaptability. The dominant implementation strategy replaces rigid mechanical connections with flexible articulations to form continuous compliant systems, as visualized in Figure 12.

Solution 8 (Derived from S2.2.4)

Discrete motor-reducer assemblies are replaced with integrated flexible drive-control joints segmented into independent drive units. Servo motors coupled with harmonic reducers are controlled by embedded servo drivers to enable precise joint motion regulation. All electronic components are encapsulated within joint housings, with serial communication ports facilitating external data transmission.

Next, the 76 standard solutions are applied from the X_2 optimization perspective based on the identical substance-field model, yielding Level 2 Standard Solution S2.1.2: Introduce an auxiliary substance-field F_2 to amplify the functional performance of the original field F_1, as shown in Figure 13.

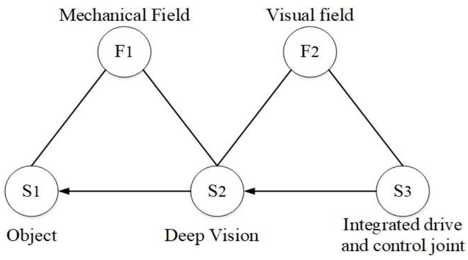


Figure 13. Introducing the Object-Field Model Diagram of the Visual Field

Solution 9 (Derived from S2.1.2).

A depth vision system is integrated to capture coordinate and pose data of target workpieces and end-effectors. The vision system transmits motion commands to drive precise grasping operations by the robotic end-effector. This upgrade expands robotic functionality while simultaneously improving motion accuracy and overall sorting throughput [24].

5. Problem Modeling and Resolution via the Little People Method

The Little People Method addresses design conflicts where individual system components cannot satisfy dual competing functional demands. In this method, malfunctioning components are abstracted into mobile hypothetical "little people" tasked with completing target functions.

The primary optimization objectives are defined first: improve robotic performance and functional versatility while constraining overall manufacturing costs. The analysis scope covers the robotic manipulator and its auxiliary hardware. Hypothetical little people are deployed to visualize conflicting functional interactions within the system, followed by restructuring their behavioral logic to achieve the design targets. as shown in Figure 14.

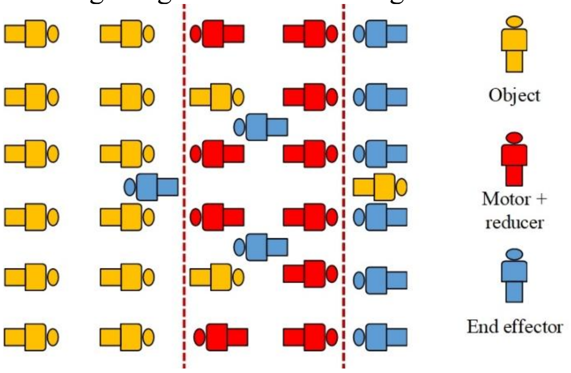


Figure 14. "Little Man Law" Modeling Diagram

First, clarify the objectives of improvement: enhance robot performance, expand robot functionality, and control costs simultaneously; second, determine the scope of operation: the robot body and its supporting hardware equipment; construct the required scenario and use "avatars" to present the interaction between both parties in the problem; then, use "avatars" to conceive the scenario form to achieve the objectives, and envision the conditions required for the "avatars" when implementing the scenario to achieve the objectives, as shown in Figure 15.

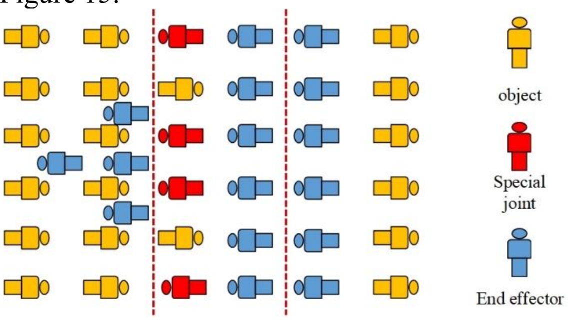


Figure 15. Improved "Little Man Law" Modeling Diagram

Scene: Target functional scenario: Develop a specialized joint structure capable of precise end -effector control with compact packaging, high operability, and simplified mechanical architecture. The joint must enhance robotic performance and expand functional range while maintaining cost efficiency.

When envisioning the target scenario, the "character" needs to undergo changes, as illustrated in Figure 16.

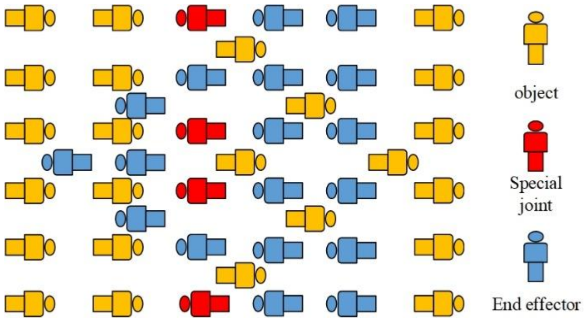


Figure 16. Adaptive "Villain Method" Modeling Diagram

Refined functional scenario: Workpiece "little people" feature irregular geometries and variable mass. End-effector "little people" require adaptive grasping capabilities, supported by high -load, high-precision specialized joint "little people" to assist automated material handling and sorting.

After iterative scenario refinement via the Little People Method, the abstract conceptual model is translated into practical engineering hardware.

Solution 10 (Derived from Little People Method Analysis)

Conventional discrete motors and reducers are eliminated. Integrated drive-control joints with high load capacity and positioning accuracy are embedded within all robotic revolute pairs. Each joint integrates servo motors, harmonic reducers, encoders, servo drive circuits, and electromagnetic brakes. The unified joint architecture supports compatibility with diverse end-effectors for multi-specification workpiece grasping and transportation, boosting robotic performance and functional diversity while controlling production costs.

6. Problem Resolution via Extended Resource Utilization

The preceding schemes satisfy baseline system requirements, yet extended resource analysis from TRIZ further refines the robotic platform. TRIZ enables comprehensive system analysis to identify root conflicts, break cognitive biases, and pinpoint core design bottlenecks, delivering innovative perspectives for system modeling and conflict resolution [25]. The ideal technical system minimizes resource input while maximizing functional output, so systematic exploitation of extended resources significantly optimizes robotic design. Extended resources span spatial, temporal, material, and energy dimensions; available resources for this robotic sorting system are summarized in Table 4.

Table 4. Extended Resource Utilization Table

Resource Category	Resource Name	Category	Usability
Extended System Resources	Camera, sensor, voice system, conveyor belt, workbench, PLC, hydraulic system.	Substance	High availability
	Electric, wind, temperature, pressure, magnetic, mechanical field.	Energy	High availability
	External space	Space	Weak Availability

With the extended resource inventory established, the substance-field model is re-analyzed to deploy standard inventive solutions. Two applicable standard solutions are identified: S2.2.4 (Improve system flexibility and adaptability) and S2.1.2 (Add auxiliary substance-field F_2 to augment original field F_1) [26].

Solution 11 (Integrated from S2.2.4 and S2.1.2)

Discrete traditional joints are replaced with flexible integrated drive-control joints. Auxiliary hardware including binocular vision modules, customized workstations, photoelectric sensors, force sensors, PLC controllers, pneumatic circuits, and voice interaction systems are integrated to form a flexible robotic sorting platform built around binocular machine vision, featuring enhanced operational safety and human-machine collaboration performance.

All generated schemes are cross-referenced against the original physical contradiction framework, with TRIZ separation principles applied to resolve the core conflict.

Core Physical Contradiction Statement.

Increasing manipulator degrees of freedom, working envelope, and auxiliary functional modules improves robotic performance, yet simultaneously raises manufacturing costs and degrades system operability and mechanical simplicity. The core conflict presents a dual demand: simultaneously increasing and reducing the manipulator's degrees of freedom, workspace range, and peripheral functional components.

System properties vary drastically across distinct spatial domains, operating timeframes, hierarchical system levels, and working conditions. The separation principle resolves this dual conflict by decoupling opposing functional demands across spatial and conditional dimensions. Corresponding inventive principles matching this separation strategy include Principle 1 (Segmentation), Principle 5 (Combination), Principle 6 (Universality), Principle 23 (Feedback), and Principle 40 (Composite Materials). Target hardware solutions derived from these inventive principles are detailed below.

Solution 12 (Synthesized from Multiple Separation Inventive Principles)

① Segmentation Principle: Decompose the robotic system into modular independent units including the manipulator body, main controller, and teaching pendant.

② Combination Principle: Integrate discrete modular units via standardized multi-mode communication and mechanical interfaces.

③ Universality Principle: Equip the core robot platform with auxiliary modules including dedicated workstations, machine vision hardware, and PLC control systems.

④ Feedback Principle: Install multi-type position and force sensors to enable closed-loop motion feedback.

⑤ Composite Materials Principle: Replace traditional cast iron manipulator links with carbon fiber-aluminum composite lightweight structures.

★The integrated hardware architecture delivers a machine vision-enabled intelligent sorting robot.

7. Evaluation of Technical Design Schemes

All proposed innovative schemes are consolidated into Table 5 to facilitate optimal solution screening. Comparative evaluation of functional performance and practicality identifies the final optimal design:

Table 5. Program Summary

Serial Number	Design Scheme	Applied TRIZ Innovation Tools	Practicality Rating
1	Construct six-degree-of-freedom sorting manipulator using integrated drive-control joints.	Inventive Principle No.15	Highly Practical
2	Install universal flanges at manipulator terminals (based on Scheme 1) to support interchangeable two-finger grippers.	Inventive Principle No.34	Highly Practical
3	Segment system hardware into independent modular units (based on	Inventive	Highly

	Scheme 2) to improve reconfigurability.	Principle No.1	Practical
4	Add one extra joint to form seven-degree-of-freedom anthropomorphic manipulator (based on Scheme 1).	Inventive Principle No.16	Low Practicality
5	Replace two-finger mechanical grippers with vacuum suction cups (based on Scheme 2).	Inventive Principle No.29	Moderately Practical
6	Install bimetallic thermal switches on joint main power circuits for overheat protection.	Inventive Principle No.37	Highly Practical
7	Upgrade six-degree-of-freedom manipulator into a multi-functional flexible robotic development platform (based on Scheme 1).	Inventive Principle No.28	Highly Practical
8	Replace traditional servo steering joints with integrated drive-control joints.	Standard Solution S2.2.4	Highly Practical
9	Mount binocular vision hardware on manipulator end-effectors (based on Scheme 2).	Standard Solution S2.1.2	Highly Practical
10	Embed high-load high-precision specialized integrated joints at all manipulator revolute pairs.	Little People Method	Highly Practical
11	Assemble flexible integrated drive-control joints with multi auxiliary subsystems to build binocular vision flexible robotic development platform.	Standard Solutions S2.2.4 + S2.1.2	Highly Practical
12	Comprehensive machine vision sorting robot design integrating all preceding schemes, synthesized from multiple inventive principles.	Principles 1, 5, 6, 23, 40	Highly Practical

A six-degree-of-freedom sorting manipulator is assembled via serial connection of independent integrated drive-control joints. Each joint embeds servo motors, harmonic reducers, encoders, servo drive circuits, and electromagnetic brakes. A universal flange mounted at the manipulator terminal supports rapid interchange of diverse end-effectors. The full platform integrates binocular vision systems, conveyor belts, customized workstations, and multi-type auxiliary sensors. Bimetallic thermal switches are installed on main power circuits to prevent thermal overload and improve operational safety. All hardware subsystems adopt modular independent layouts, which are mechanically and electrically integrated to form a complete machine vision-based intelligent sorting robot platform.

The optimal design scheme derived from TRIZ theoretical analysis is prototyped as a machine vision sorting robot experimental platform, shown in Figure 17, for functional verification testing.

Figure 17. Experimental Platform for Sorting Robot Based on Machine Vision

8. Conclusion

This paper completes a full-process innovative design workflow for intelligent sorting robots entirely supported by the TRIZ theoretical framework. Preparatory analytical tools including the Nine-Screen Method, Three-Axis Problem Analysis, and Causal Chain Analysis are deployed to disassemble system functions and trace root causes of performance defects. Component relationship matrices and functional modeling identify core limitations of conventional industrial sorting robots: oversized overall footprint, excessive self-weight, restricted working envelope, insufficient safety for human-machine collaboration, poor end-effector compatibility, messy external wiring, and low integrated control performance. Multi-layered TRIZ toolkits are applied sequentially to resolve the identified engineering conflicts:

Two sets of technical contradictions are formulated based on the 39 standard engineering parameters. The contradiction matrix matches applicable inventive principles including Dynamization, Segmentation, Discard and Recover, and Mechanical Substitution to generate multi-dimensional hardware improvement schemes.

Physical contradictions between performance enhancement, manufacturing cost, and mechanical complexity are resolved via substance-field modeling and the 76 standard solutions. Flexible integrated drive architectures and auxiliary vision fields are introduced to optimize system interactive performance.

The Little People Method visualizes conflicting grasping operations during human-machine sorting tasks, confirming integrated drive-control joints as the core optimization component.

Extended system resources covering spatial volume, multi-type sensors, and multi-physical energy fields are fully exploited. Separation inventive principles including Segmentation, Combination, Universality, Feedback, and Composite Materials are integrated to synthesize a unified optimized design solution.

Comparative practicality evaluation across all candidate schemes confirms the optimal design architecture:

A six-axis serial lightweight manipulator replaces discrete motor-reducer assemblies with integrated drive-control joints embedding servo motors, harmonic reducers, encoders, drive circuits, and electromagnetic brakes. Carbon fiber-aluminum composite links reduce overall manipulator self-weight. Universal quick-change flanges at manipulator terminals support rapid switching between pneumatic suction cups and electric mechanical grippers. Binocular vision, force sensors, photoelectric sensing modules, and voice human-machine interaction systems are fully integrated. Bimetallic thermal switches on main power circuits deliver active overheat protection. The full system adopts split modular layouts and eliminates fixed safety guardrails to realize barrier-free collaborative sorting between humans and robots. The proposed design expands manipulator degrees of freedom, improves sorting adaptability and intelligence, simplifies internal wiring, and reduces overall installation footprint. This research delivers standardized innovative design guidelines for lightweight collaborative intelligent sorting robotic platforms.

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