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Original R&D-Driven Mechanical Innovation Design Method for Mechatronic Products

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Abstract

An engineering thinking-driven detailed development framework for mechatronic products is established, which providing systematic guidance for novices to comprehend the core logic and methodology of original product R&D. A principal scheme methodology integrating hierarchical functional decomposition with reverse-solving synthesis is proposed, which demonstrates that the planning and precise implementation of mechanism process actions are the cornerstones for realizing product functions and conducting original design. The developed reverse-sequence design method, end-to-center priority principle, and component hierarchy criteria are effective for detailed structural design execution. The knowledge system required for the original research and development of products was constructed in reverse through detailed design methods and ideas for mechanical structures.

Keywords: *Mechatronic products; Original innovation; Innovative design; Mechanical design methodology*

1. Introduction

University faculty specializing in mechanical engineering typically focus on theoretical innovation while lacking practical experience in original product development. Conversely, senior engineers with substantial R&D expertise rarely engage in systematic educational program design. This professional segregation creates significant pedagogical challenges: how to establish a mechanical innovation knowledge system oriented toward original mechatronic product development, and how to articulate engineers' cognitive patterns during original R&D processes.

Literature Review[1] developed a mechanical design pedagogy featuring "faculty-guided knowledge construction through interactive engineering object design". [2] introduced artificial intelligence, particularly expert systems, into full-cycle user design processes with fuzzy mechanical design theory applications. [3] proposed a six-dimensional teaching framework for engineering courses. [4] established normalized indicator matrices for optimal design scheme selection. [5] created integrated engineering education merging theory-practice, analysis-synthesis, and learning-creation. [6] constructed a tri-integration talent cultivation model combining specialized courses, capstone projects, and research training. [7] implemented three systemic approaches: integrated multimedia courseware development, modular teaching based on system design principles, and comprehensive assessment. [8] investigated four mechanical innovation methodologies: functional principles, ergonomics, intelligent systems, and reverse engineering. [9] formulated a knowledge-fusion mechanical design teaching method. [10] identified design synthesis and creation as engineering's essential paradigm. Textbooks like *Mechanical Design: An Integrated Approach* by Ansel C. Ugural and *Product Design* by Kevin N. Otto & Kristin L. Wood demonstrate superior systematicity compared to Chinese counterparts, yet lack dedicated focus on original mechatronic product development methodologies.

Current literature survey reveals that professional education has not yet established a complete knowledge system guided by original R&D of mechatronic products. The prevailing mechanical design education system exhibits critical deficiencies, particularly in teaching the design methodologies and engineering thinking patterns essential for original product development. This knowledge gap results in undergraduates and even graduate students demonstrating inadequate capability to systematically execute design tasks, with many remaining incompetent in conducting original mechatronic product R&D upon graduation.

2.Relationship Between Knowledge System and Mechatronic Product Development

As shown in Figure 1, mechatronic product development constitutes the comprehensive application of interdisciplinary knowledge from mechanical engineering, control science and engineering, and related disciplines. Complex R&D processes require extensive knowledge integration and team collaboration. Professional education cultivates diverse talent types, primarily categorized into engineering technology-oriented professionals and academic research-oriented professionals, with their training programs requiring distinct differentiation. Within engineering technology education, further classification and stratification are necessary: product R&D personnel and production technology personnel demand differentiated training schemes with clearly distinguished emphases..

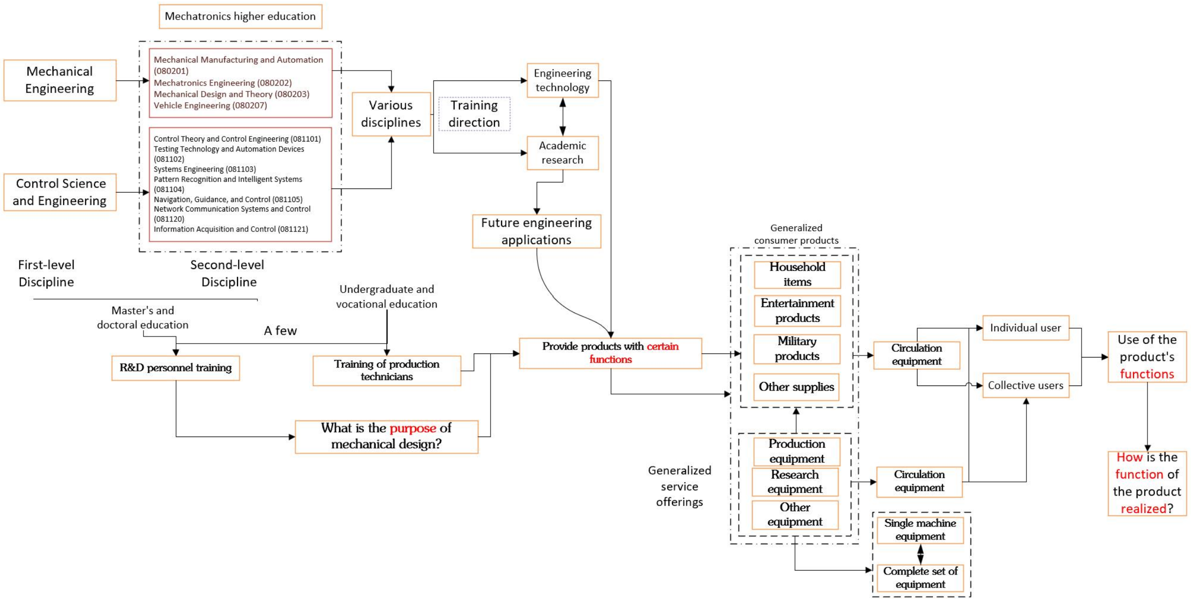

Figure 1: Relationship Between Knowledge System and Electromechanical Product R&D

3. Processes and Methods for Original R&D of Mechatronic Products

The original R&D process for mechatronic products is illustrated in Figure 2. During the preliminary design phase, sales personnel typically propose design tasks and requirements analysis, while technical staff must systematically analyze these demands to clarify product functionalities and design specifications, subsequently conducting functional decomposition and solution derivation. The intermediate design phase necessitates rigorous motion coordination among multiple mechanisms. In the final design stage, comprehensive consideration of various influencing factors is required during system integration design, with particular emphasis on manufacturing processes for individual components and force transmission characteristics between components and assemblies during detailed part design.

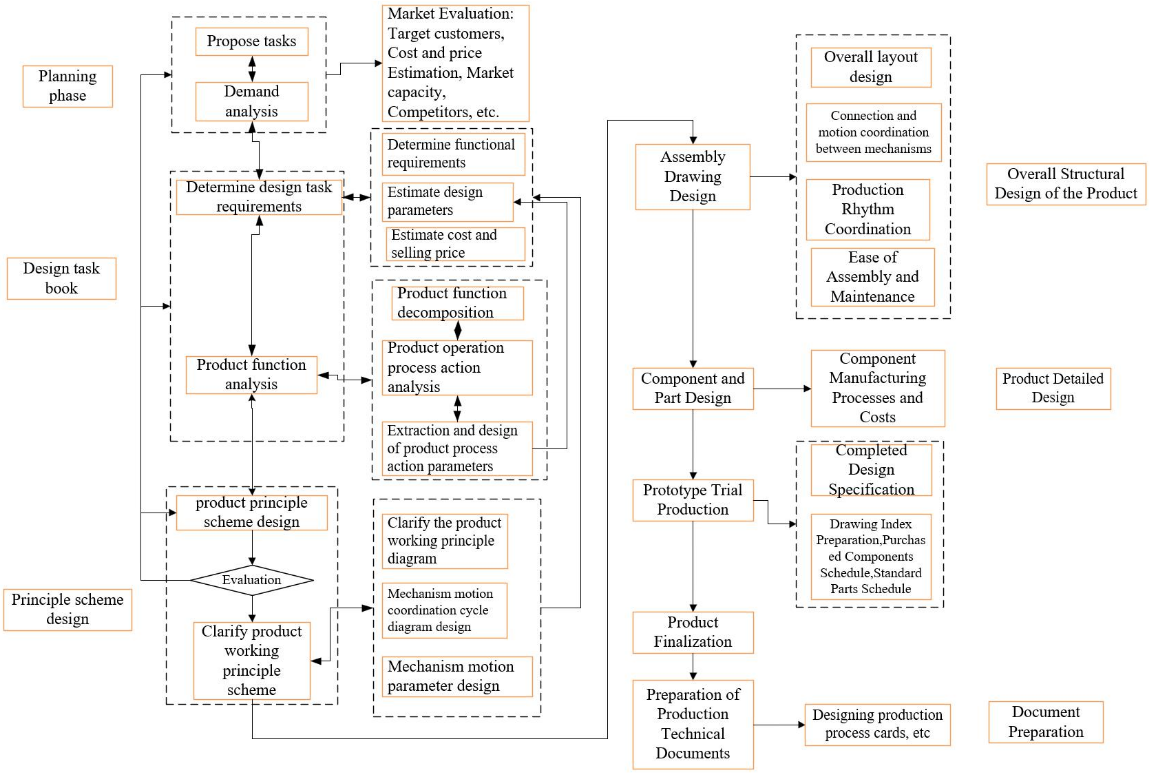

Figure 2: Original R&D Process of Electromechanical Products

3.1. Conceptual Design Methodology and Approach

The conceptual design phase of mechatronic products represents one of the most innovative processes in R&D. While analyzing requirements allows relatively straightforward determination of the product's overall functionality, and while some educators advocate function-based design approaches, few have systematically investigated methodologies for executing functionality-driven development.

As shown in Figure 3, product functionalities exhibit varying complexity - ranging from singular to highly sophisticated - necessitating original developers to establish universal strategies and systematic workflows. The established methodology involves multi-level functional decomposition: starting from the overall functionality, designers progressively break it down into primary sub-functions, secondary sub-functions, until reaching irreducible m-th level sub-functions. At this stage, critical analysis focuses on identifying the required process motions and parameters for each terminal sub-function's implementation - specifically determining what mechanical actions and technical specifications can achieve the targeted functionality, which essentially constitutes the mechanism selection process.

Through reverse integration of solutions for lower-level sub-functions, higher-level solutions can be systematically synthesized. This hierarchical integration generates multiple candidate solutions at each functional level, followed by rigorous optimization and evaluation to identify optimal conceptual schemes. During this process, numerous proposals are typically eliminated due to critical constraints including workspace limitations, precision requirements, structural rigidity, and economic viability, often resulting in few ideal candidates remaining. A fundamental principle requires particular emphasis: precise planning and accurate implementation of mechanism process motions form the essential foundation for both functional realization and subsequent detailed design phases.

Although this methodology proves effective for original product development, it remains conspicuously absent from current professional education systems.

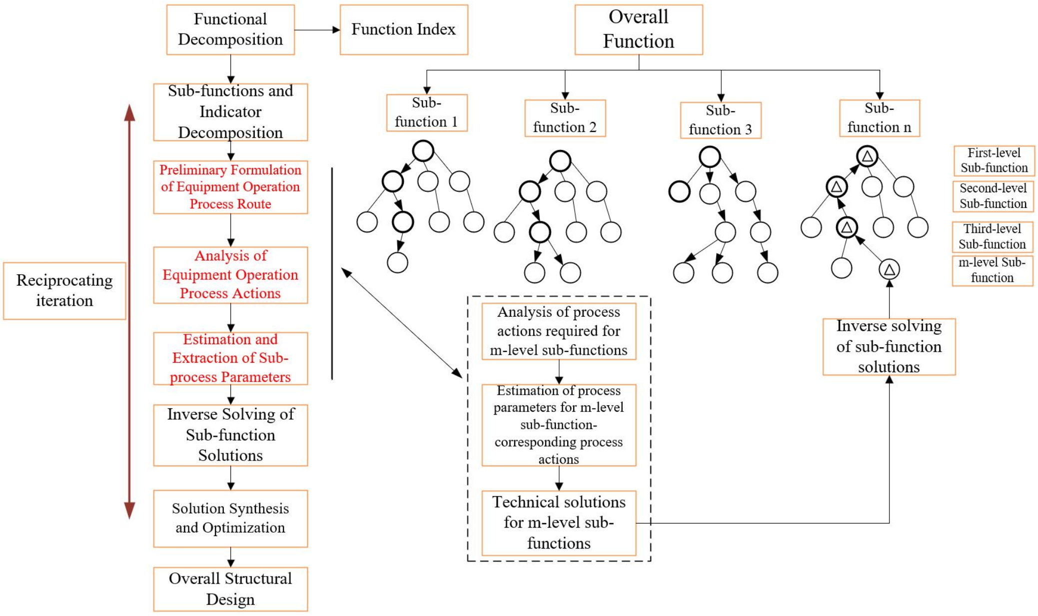

Figure 3: Methods and Approaches for Conceptual Design

3.2. Detailed Structural Design Methodology and Approach

Following the establishment of the conceptual scheme, detailed structural design implementation proceeds as shown in Figure 4. This phase requires consideration of multiple interrelated factors that may exhibit complex interactions and mutual influences, necessitating comprehensive evaluation of performance metrics versus comprehensive cost considerations during decision-making processes. The design execution must strictly adhere to fundamental engineering principles while mandating rigorous theoretical calculations for critical load-bearing components, ensuring each design decision is supported by verifiable analytical evidence. Only through this methodical approach can the original design intent be accurately translated into functional physical implementations.

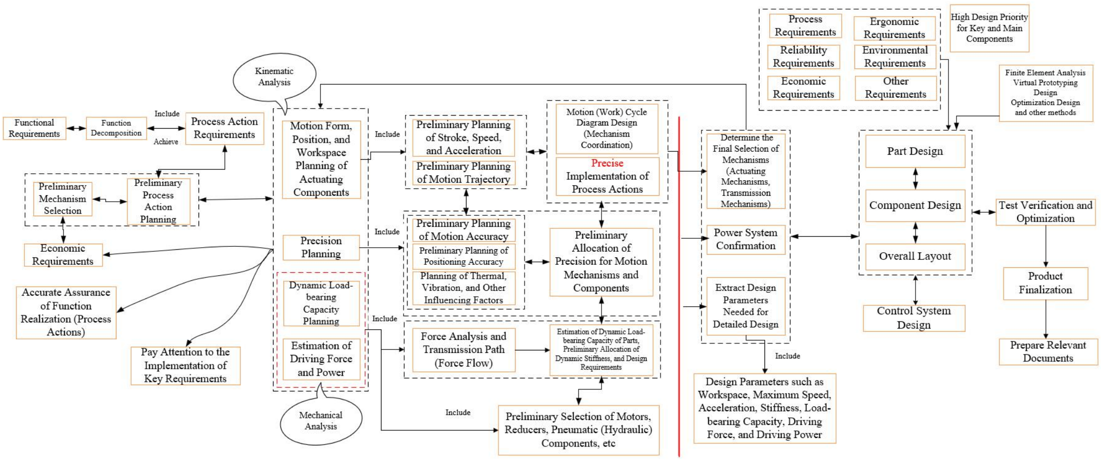

Figure 4: Detailed Mechanical Structure Design Methodology

The knowledge framework essential for developers, as illustrated in Figures 1-4, reveals that conventional professional education overemphasizes kinematic computations (trajectory planning, workspace analysis) and mechanical calculations (driving forces, power requirements), while critically neglecting precision planning, force flow optimization, and motion coordination design in Figure 4.

When equipped with this knowledge system, developers typically adopt two principal design implementation strategies:

●Complete execution components and mechanisms first.Execute the design of functional components and actuation mechanisms prior to developing other subsystems. The execution components within actuation mechanisms serve as the critical elements determining product functionality through their process motions and operational parameters. Transmission mechanisms between power sources and actuators must meet specified requirements in generalized forces, precision, and stiffness.

●Prioritize principal mechanisms over auxiliary ones.Design principal mechanisms before auxiliary mechanisms, ensuring primary design requirements take precedence.

●Design critical components before auxiliary parts. In the design process of individual mechanisms, implement the design sequence as: critical components first, followed by primary components, then auxiliary components. When conflicting requirements occur, adhere to the design assurance priority hierarchy: critical components > primary components > general components.

●Implement standardized modular design.Adopt standardized, modularized, and serialized design philosophies to enhance manufacturing efficiency.

Design Guiding Principles：

●All auxiliary mechanisms exist to serve the functional components within actuation mechanisms.

●Stiffness primarily serves precision requirements in most design scenarios.

●Maintain force flow (power transmission) awareness throughout the entire design process.

●Prefer simplicity in design solutions whenever feasible.

●Design decisions for high-speed, highly dynamic equipment must be grounded in theoretical calculations rather than empirical assumptions.

4. Practical Cases

4.1. Case Study in Functional Decomposition: Metal-Cutting Milling Machine

As illustrated in Figure 5, the functional decomposition process of a metal-cutting milling machine begins by breaking down its overall milling functionality into multiple primary sub-functions (Level 1) and numerous secondary sub-functions (Level 2). Terminal sub-functions undergo detailed analysis and solution derivation, followed by reverse integration to synthesize the comprehensive system solution.

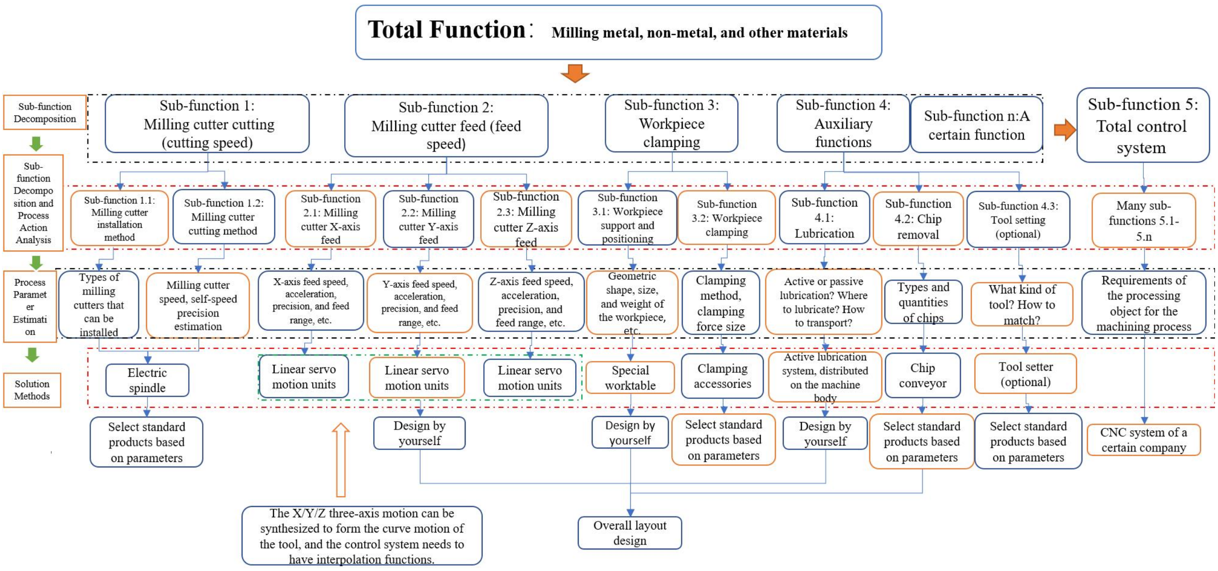

Figure 5: Case Study on Functional Decomposition of a Milling

4.2 .Product Development Case: Faculty-Student Collaborative R&D Projects

Applying the aforementioned methodology, faculty members have successfully executed multiple original product innovation R&D projects from inception. Representative faculty-developed systems include an aircraft exterior coating system and a tube bending polishing production line, as shown in Figures 6, 7, and 8. Student teams have correspondingly produced innovative designs documented in Figures 9, 10, and 11.

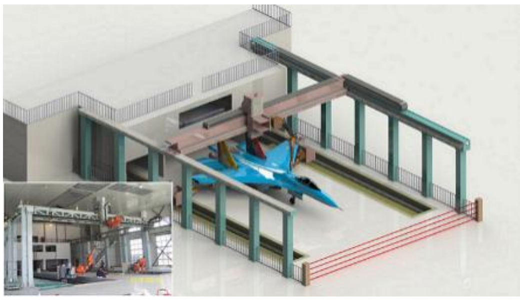

Figure 6. Aircraft external surface coating system.

Figure 7. Parallel machine tool.

Figure 8. Bent tube polishing production line

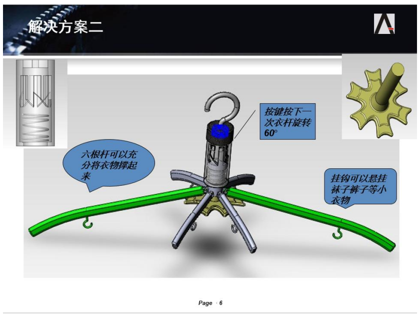

Figure 9. Multi-functional clothes rack

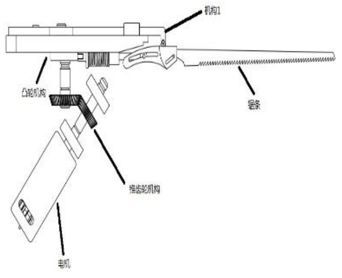

Figure 10. Angle-adjustable electric saw

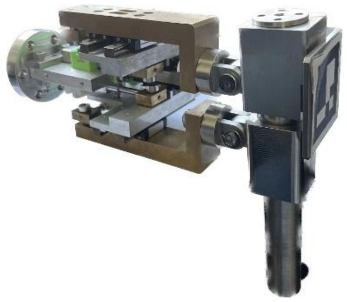

Figure 11. End effector of orthopedic surgical robot

5. Conclusion

Fundamental product development requires systematic hierarchical functional decomposition and reverse-solving integration based on thorough design requirement analysis, forming the cornerstone for both conceptual scheme formulation and functional realization through precise mechanism process motion planning. During detailed design phases, while engineers typically maintain rigorous computation of kinematic parameters (motion patterns, dynamic postures, workspace), insufficient estimation of dynamic load and stiffness effects on actuator positioning errors frequently compromises process motion accuracy. Structural design prioritization necessitates multi-factor equilibrium analysis, adhering to the principle of "maximizing simplicity and cost-efficiency while fulfilling specifications". The established reverse-sequence methodology and end-first design approach, coupled with focused development of critical load-bearing components, prove effective for component-level implementation.

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