1

Introduction

1.1 Introduction

Mechatronics is an engineering discipline that brings multiple conventional disciplines including *mechanical*, *electrical*, *electronic*, and *information engineering* together to optimize the solutions to various engineering problems. Originally, the concept of Mechatronics was coined by a Japanese Engineer Tetsuro Mori from the words of **mecha**nical engineering and elec**tronics** in 1969. Nowadays, the coverage of modern mechatronics has gone far beyond from the integration of conventional engineering disciplines to the extension to many new disciplines such as *artificial intelligence* (AI), *telecommunications*, and *cybersecurity* as long as emerging disciplines can be integrated to enhance the capabilities of mechatronic systems.

In comparison with conventional systems, a mechatronic system consists of a set of multiple mechatronic components that exhibit multidisciplinary behaviors. Therefore, the design of a mechatronic system must be performed concurrently, so that design constraints in multiple disciplines can be modeled, analyzed, and satisfied simultaneously. From this perspective, mechatronics is also viewed as *a philosophy* where a system design associated with multiple disciplines is performed concurrently to seek integrated solutions to complex engineering problems. *Mechatronics* becomes a growing discipline that has been, and it will be evolve continuously with emerging technological advancements in *Materials*, *Science*, *Processes, Engineering*, *Integration technologies*, and *Information Technologies* (ITs). Most of the classic books on mechatronics have lagged to reflect recent advancements, especially in ITs. In the following sections, the trends of the developments in engineering designs, integration technologies, and ITs are discussed with a focus on their impact on Mechatronics.

1.2 Growing Complexity of Engineering Designs

Engineering design is to formulate c*ustomer's requirements* (CRs) into a design problem with specified constraints and objectives and develop a *design solution* (DS) that can satisfy CRs optimally. A complete engineering design usually includes *design for manufacturing* (DfM) and *design for assembly* (DfA) where the constraints of manufacturing or assembling processes are taken into considerations at the phases of manufacturing and assembling, respectively. By DfM and DfA, a virtual model can be used to analyze system behaviors, predict system outcomes, and verify if all design

Mechatronics for Complex Products and Systems: Project-Based Design Approaches for Robots, Cyber-Physical Systems, Digital Twins, and Other Emerging Technologies, First Edition. Zhuming Bi.

Companion website: www.wiley.com/go/bi/mechatronics

constraints can be satisfied. These reduce the needs of iterations when design defects are identified and fixed at late phases of system development.

Since the information and knowledge about a product or system are accumulated gradually when its design process proceeds, the constraints involved in later design stages cannot be verified until relevant information becomes available. This becomes an obvious reason why an engineering design process is naturally iterative. In other words, the constraints that are ignored in early design phases must be verified later. In such a way, a design space with tentative solutions should be continuously refined to satisfy more and more constraints until all of them are fully satisfied.

It is desirable that less number of iterations is needed to transform a virtual model into a physical model. This implies that design iterations all occur in the virtual world with no additional cost on physical prototyping. The finalized virtual model is converted into its physical model correctly at the first time. It is referred as *First-Time Right* (FTR) practice (Bi and Wang 2020). The methodologies for engineering designs are being advanced continuously to cope with the growing complexity of products or systems in their lifecycles from design to manufacturing, assembly, application, and to disposal. Figure 1.1 shows the trend of increasing complexity of engineering designs from the perspective of manufacturing (Alkan et al. 2018). The growth of the complexity of a manufacturing system can be observed in the aspects of *products*, *enabling technologies*, and *business environments*.

Figure 1.2 shows the dimensions of complexity in engineering designs that are dependent on those of products, technologies, and degrees of dynamics and uncertainties. The complexity of each aspect could be further decomposed when the solutions to corresponding functional

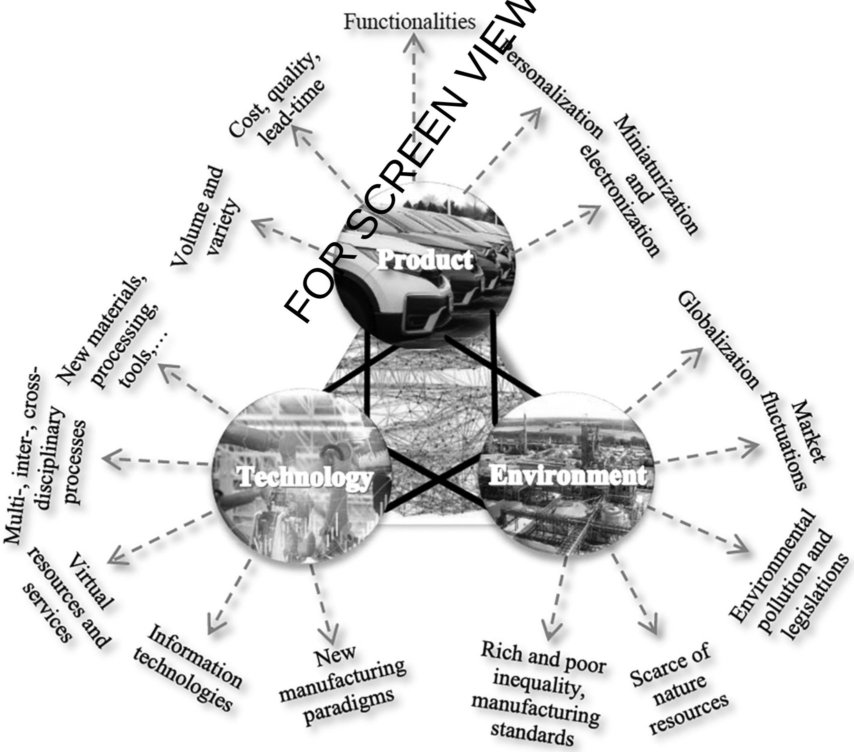


Figure 1.1 Dimensions of growing complexity of engineering designs

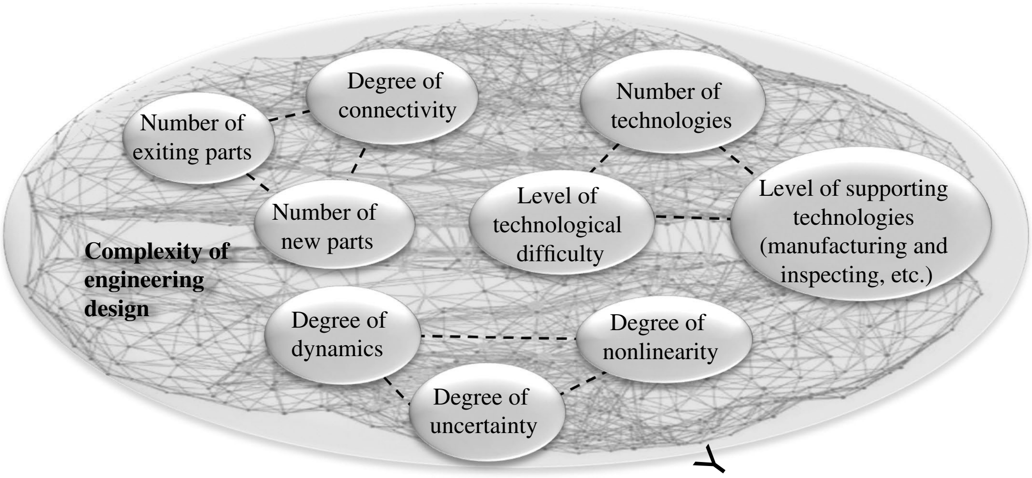


Figure 1.2 The dimensions of complexity in engineering design: products, technologies, and degrees of dynamics and uncertainties

requirements are not available. Accordingly, the complexity of products depends on many factors including the number of parts and assemblies, the degrees of connectivity, nonlinearity, and dynamics, the number of accessible technologies, and the levels of technological difficulties and assistive technologies.

1.2.1 Products

The complexity of a product has been measured by numerous factors such as *types* and *numbers* of constitutive parts and components, *types* and *numbers* of the processes to manufacture parts and assemble parts into components, *variants* and *volumes* of products, and system performance criteria such as *quality*, *lead-time*, *cost*, *lifespan*, and *after-sales service*s of products (Orfi et al. 2011). Researchers agree that the scale and the complexity of modern products have been increasing greatly. Figure 1.3 shows some examples of main variables that affect the complexity of products (i.e., lawn mowers, grand pianos, cars, and airplanes); some factors such as *numbers*, *types*, and complexity of constitutive components contribute to the complexity of products directly. It seems clear that a product with a high-level complexity involves a high number and types of simple or complex parts and components.

The growing complexity of modern products can be evidenced by the evolution of various product families. Adamsson (2005, 2007) used the examples of wiring harnesses to show an increase in the complexity of automotive products. An automobile in 1949 had ~60 contact points with ~40 wires. An automobile in 1990 had around 3800 contact points and used approximately 1900 wires with a total length of ~3 km. An automobile in 1999 used 110 electric motors and 60 electronic control units (ECUs). Three data bus systems were used to support information integration and data exchanges. BeyondPLM (2018) discussed the trend of the ever-increasing complexity of modern products; it was associated with the *number of configuration items* (NICs). A typical mechanical system, mechatronic system, and large-scale integrated system have typically less than 10^3, 10^3–10^5, and over 10^8 NICs, respectively.

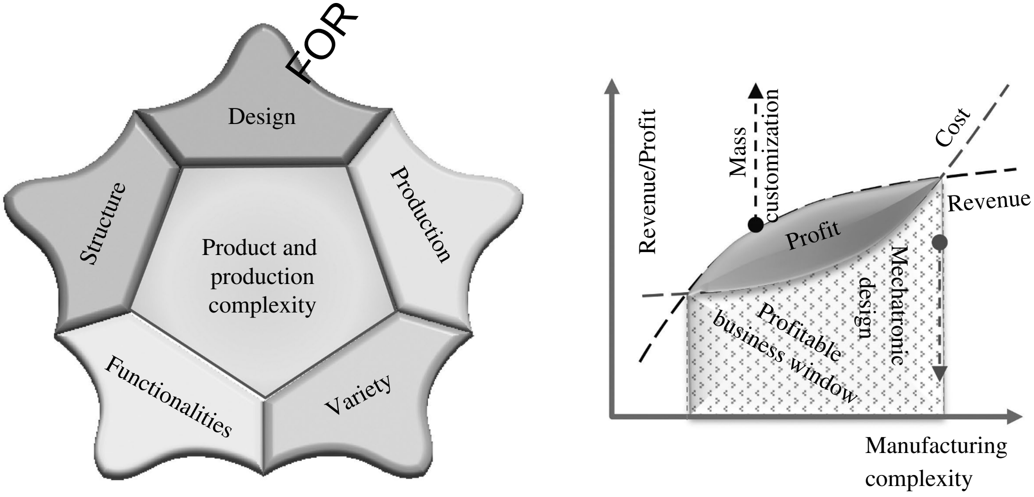
Product complexity is related to numerous factors in manufacturing and production such as design, development, manufacturing, assembly, and supply chain management. As shown in

(a) Gripper (b) Machine (c) Piano (d) Automobile (e) Transport plane (C-5A) (f) Airplane (747-400)

Figure 1.3 Examples of product complexity versus numbers of parts

Figure 1.4a, product complexity was modeled in the dimensions of *designs*, *manufacturing processes*, *functionalities*, and *varieties*. A manufacturer can be profitable only when the complexity of products and associated processes can be managed by *mechatronic design* at the design phase and by *mass customization* at the manufacturing phase appropriately. As shown in Figure 1.4b), the more products a company makes, the higher revenue the company can gain. On the other hand, making more product variants implies the increase in the complexity of the corresponding production system, thus affecting the productivity, lead time, and cost reduction. Production cost increases monolithically with the number of products and variants. Knowing customers' needs becomes a strategic resource to enterprises now. However, there is a limited business window for enterprises to make products to meet customers' needs in a profitable way. To expand a profitable business window, efforts can be made to increase the production revenue by making more products through mass customization and reduce the development cost by increasing system efficiency such as through mechatronic design.

With the need for more versatile and advanced products, the number and types of parts and the complexity levels of parts are expected to be increased continuously. The complexity of products due to other factors, such as volume and variety in enterprise and personalization, has been thoroughly discussed by other scholars (Bi et al. 2021a). The survey of over 246 engineers by Rowe (2019) concluded that the complexity of products was continuously increasing, and design



(a) Product and production complexity (b) Profitable business window

Figure 1.4 Main dimensions of product complexity and profitable business window methodologies need to evolve to manage the complexity effectively. Ninety-two percent of the engineers reported that in the last five years, the products had increased the complexity in various aspects such as intricate mechanical designs, embedded electronics, and newly introduced materials and processes. It was found that the main causes of increased products' complexities were attributed by intricate mechanical design (57%), more electronics (47%), adoption of different materials (43%), reduced reductions (40%), system integration (30%), compacted sizes (30%), embedded software (26%), pressure for AI and smart things (17%), and more microprocessors (16%).

1.2.2 Manufacturing Technologies

Manufacturing technologies are the collections of methods, skills, techniques, and processes used to make goods or provide services to meet users' needs. Three primary factors of a manufacturing technology are *materials*, *manufacturing processes*, and *systems* (Groover 2020). More and more new alternatives for materials, processes, and systems become practically available, and this leads to high-level complexity in evaluating, selecting, and using advanced manufacturing technologies.

Advanced products or systems usually have high requirements of materials such as extremely high strengths, low weight, long durability, and better self-healing and resilience. Numerous research efforts have been made to explore high-performance materials such as new cements and composites, nanomaterials, optical materials, biomaterials, lightweight materials, and biodegradable materials (Hutagalung 2012; Grant 2013). Using advanced materials helps enhance the performance of products greatly. For example, an average percentage of composite materials in airplanes increased from 10% to 15% in 1980 to over 50% in 2015 (GeneralPlastics 2021). New methods have been developed to design, compose, and customize composite materials for given applications. Traditionally, materials' characterizations rely mainly on experiments, which are time consuming and expensive. The rapidly developed Computing Science offers the capabilities for virtual designs of new materials through *Machine Learning* (ML), *Big Data Analytics* (BDA), fuzzy logic, and Soft Computing (Babanli et al. 2019). Technologies for advanced materials are classified into basic sciences, generic technologies, and proprietary technologies; the innovations in advanced materials are critical since new materials (1) contribute to manufacturing applications greatly, (2) bring the opportunities to span new enabling technologies, (3) address key socio-economic challenges, (4) add high values to manufacturing businesses, and (5) be compatible to innovative infrastructure (Featherston and O'Sullivan 2014).

ITs play irreplaceable roles in (1) automating manufacturing processes and (2) supporting decision-making activities at all domains and levels of manufacturing businesses. With the advances in the computer hardware and software and information infrastructures, ITs have greatly proliferated from standalone mechanization to *computer-aided drawing*, *computer-aided design* (CAD), *computer-aided engineering* (CAE), *computer-aided manufacturing* (CAM), *supply chain management* (SCM), *enterprise resource planning* (ERP), computer-integrated manufacturing (CIM), argument reality (AR), digital twins (DT-Is), cloud computing (CC), *Big Data analytics* (BDA), and recently to *digital triad*-II (DT-II) and *Internet of Digital Triad Things* (IoDTT) (Bi et al. 2021a, 2021b).

The continuous evolution of automation and ITs has made it possible to advance manufacturing paradigms from *mass production* to *lean production*, *flexible manufacturing*, *CIM*, *mass customization*, and recently *sustainable manufacturing*. This provides the possibility for enterprises to select and implement certain manufacturing paradigms for their specific applications (Bi et al. 2014a, b). Moreover, *Internet of Things* (IoT) offers an effective mechanism for enterprises to utilize virtual manufacturing resources dynamically, and this adds a new dimension to the complexity of manufacturing systems.

1.2.3 Business Environments

Manufacturing environments used to be steady, in the sense that enterprises can define the boundaries of their manufacturing systems clearly, and any changes in operating their manufacturing systems are predictable. Manufacturing operations are planned, scheduled, and executed within manufacturing systems with few disturbances from environments.

However, today's manufacturing businesses become more and more closely related to manufacturing environments. Business environments have been gradually complicated and become dynamic greatly due to a number of factors: (1) global manufacturing capacities have exceeded the overall capacities required to meet users' needs of products; this has led to high diversifications and fluctuations of product demands and fierce competitions among manufacturers across nations and regions. (2) Environmental issues such as global warming, population, scarcity of natural resources, and deterioration of global living conditions become ever worsening. More and more regulations and laws have been developed for the industries to alleviate environmental challenges. Manufacturing enterprises are highly pressured to minimize the environmental impact by expanding manufacturing businesses over product lifecycles from raw materials, to design, manufacturing, assembly, and use of products, and finally to disposal and recycling (Bi 2011). (3) The development trends of human society have also increased the complexity of manufacturing businesses in the sense that full automation is impractical for most manufacturing enterprises. These trends include the aging of population, lacking of experienced workers, and growing inequality of the rich and poor.

1.2.4 Engineering Design

Mechatronic design is typically multidisciplinary and deals with multiple disciplines to meet economic, environmental, and social needs (Adamsson 2007; Strong 2021). Modern products and systems are mostly complex and sophisticated in terms of their intelligence levels and information-relevant contents. It becomes necessary to adopt some global and integrated approaches to deal with the design activities from a very early stage and throughout the whole design lifecycle (Defoort et al. 2012). Designs of a complex system are often open ended and ill defined, and the design content goes far beyond the scope of traditional individual disciplines. The trend of system complexity has evolved from *multidisciplinary* to *interdisciplinary* and to *transdisciplinary*. Engineers are required to work both within and outside the boundaries of their own disciplines. They should be trained to understand, synthesize, analyze, and apply knowledge and skills from disciplines other than their own (Beemt et al. 2020). Telenko et al. (2016) discussed the need to solve multidisciplinary problems throughout the curriculum, and they proposed the pedagogical underpinnings to integrate design experiences and multidisciplinary learning into engineering curricula. With the rapid development of ITs, mechatronic design turned out to be a vital approach to solve various multiple disciplinary engineering problems (Alciatore 2019).

As illustrated in Figure 1.5, the complexity of an engineering design depends on the *functional requirements* (FRs) associated with products, manufacturing processes, and business environments. The more complex the products, manufacturing processes, or business environments are, the more complex the corresponding engineering design is. Moreover, the integration of products, manufacturing processes, supply chains, and planning and controlling as a comprehensive manufacturing system brings new constraints for correspondences, compliances, and dependencies among system elements. The complexity of engineering design can be increased exponentially due to the comprehensive effects of the increasing complexities of products, manufacturing processes, and business

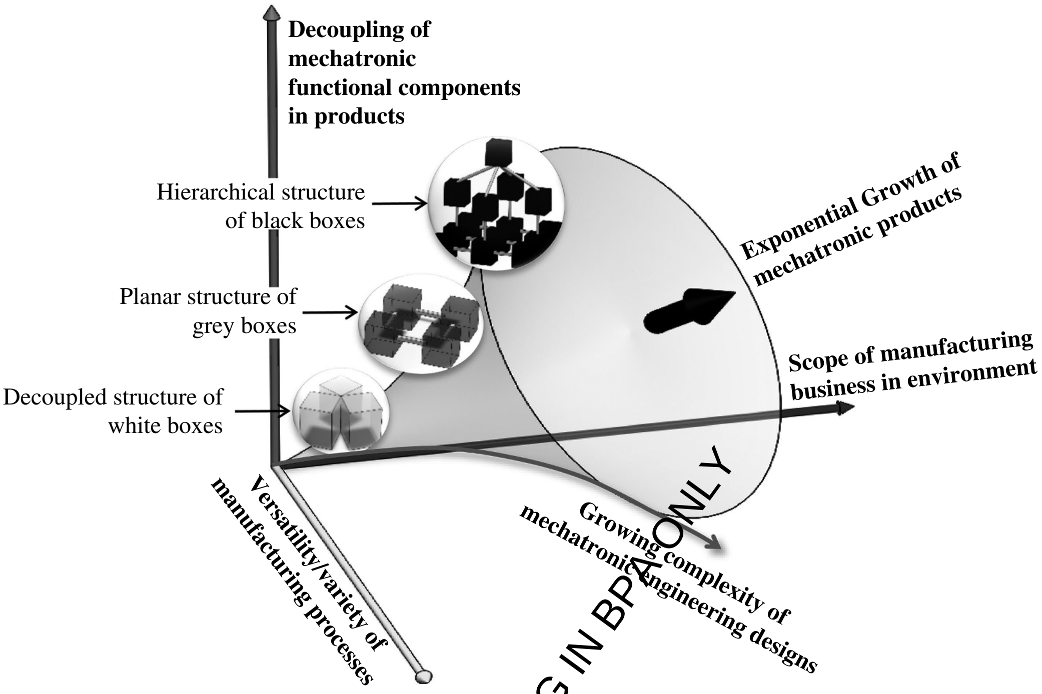


Figure 1.5 Growing complexity of mechatronic engineering designs

environments discussed in Sections 1.2.1, 1.2.2, and 1.2.3. Effective design methodologies are needed to deal with the ever-increasing complexity of modern engineering designs.

1.3 Integrated Engineering Design

In mechatronic design, the complexity of a mechatronic system can be measured by the numbers and types of FRs related to products, manufacturing processes, and business environments. Moreover, these multidisciplinary FRs are strongly coupled, and the DSs to these FRs have to be developed concurrently in such a way that (1) the design space for all potential solutions is not reduced due to a sequential design procedure and (2) all of the design constraints in these disciplines can be satisfied simultaneously (Bi 2002). As shown in Figure 1.6, raw materials are transformed into final products through a series of manufacturing processes; and the theories, design knowledge, and tools in different disciplines are utilized to implement manufacturing transformations. However, design constraints and outcomes in one discipline can strongly be coupled with those in other disciplines, since all of them are coupled to physical objects or processes in the material flow.

Three fundamental ways to deal with changes and complexity are (1) using an integral component with its flexibility of adapting certain changes, (2) using a modularized structure where different numbers and types of modules can be selected and assembled into various system configurations for different functions, and (3) using modularized structure with adjustable components as part of modules. Since a modularized structure has been proven in its great effective in using topological parameters to deal with changes, an integrated engineering design methodology should be capable of decomposing system-level FRs into loosely coupled sub-FRs, so that integrated

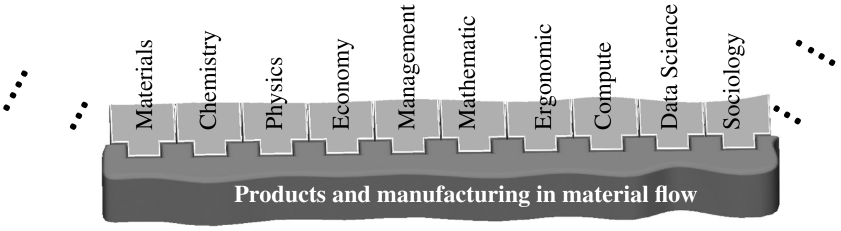


Figure 1.6 Couplings of multidisciplinary behaviors in products and manufacturing

solutions can be developed for individual sub-FRs, respectively. Figure 1.7 describes the scenario of using an integrated engineering approach to designing a complex product or system. Five main tasks of integrated engineering design are (1) decomposing system-level FRs into sub-FRs until corresponding DS is identified to each of sub-FRs, (2) performing virtual design to identify DSs for all sub-FRs, (3) developing physical functional modules for required virtual DSs, (4) selecting and assembling modules into a system configuration to meet the required FRs, and (5) developing the control system to integrate and coordinate the controls of decentralized modules in physical implementation. It is worth to note that conventional multiple-disciplinary designs emphasize on task 3 in Figure 1.7.

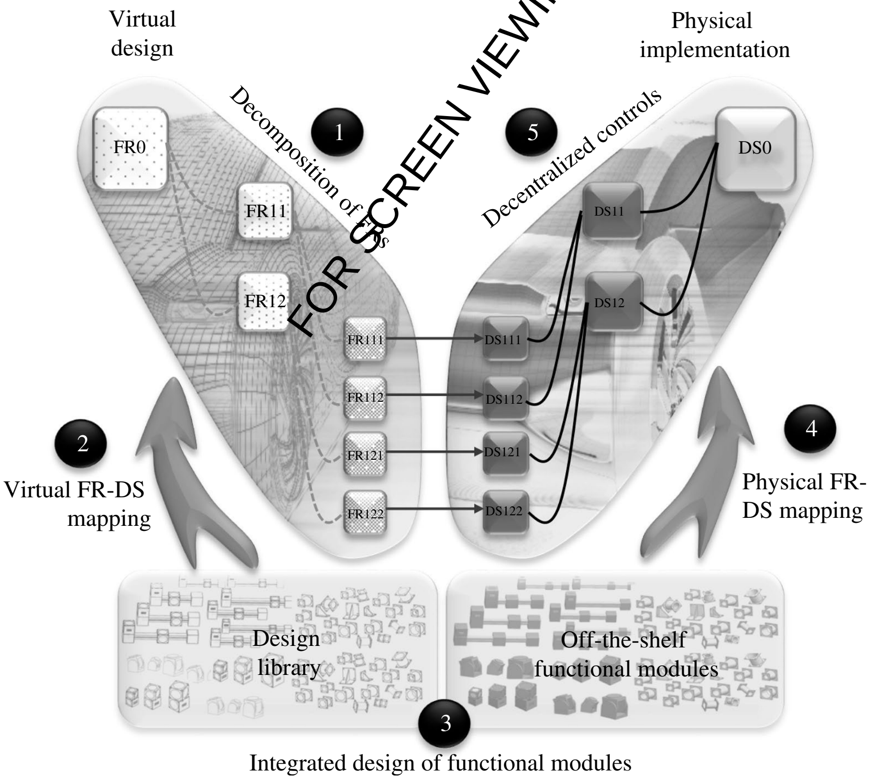


Figure 1.7 Scenario of using an integrated design method for complex product or system

1.4 Mechatronics for Multi- or Interdisciplinary Designs

With the saturation of globalized manufacturing capacities, companies are facing some fierce competition in advancing their products and systems. A mechatronic design helps reduce the complexity of objects significantly (AIMSek 2024). DE247 (2024) gave a few examples of using the mechatronic methodologies to deal with product complexity: (1) adopting the mechatronic design method reduced a half number of parts from Boeing 767 to Boeing 787 and the design was actually performed in a distributed and decentralized environment with 5400 suppliers in 38 states in the United States and 19 counties. (2) A conventional fuel nozzle with 18 parts was simplified and fabricated as a single component by additive manufacturing at the General Motors (GM). (3) An iPhone camera consisted of over 200 parts, and it was developed collectively by a team of over 800 members.

van der Roest (2017) discussed the evolution of enabling technologies in dealing with the increasing complexity of products. As shown in Figure 1.8, conventional mechatronic design is at one phase of technological development, where electric and electronic components are embedded in mechanical components as an integrated system. With the continuous increase of product complexity, the scope of mechatronic design has to be expanded greatly to integrate dynamic resources such as smart things, cyber-physical systems (CPSs), and dynamic services in distributed and decentralized environments.

Products were traditionally dominated by mechanical designs for motion and power transforms; however, more and more electronic and software components are integrated on mechanical structures as mechatronic products and systems. Taking the example of automobile industry, the number of electronic components has increased steadily. Over 80% of new functions were implemented by mechatronic components, and around one-third of the total cost of products was spent on

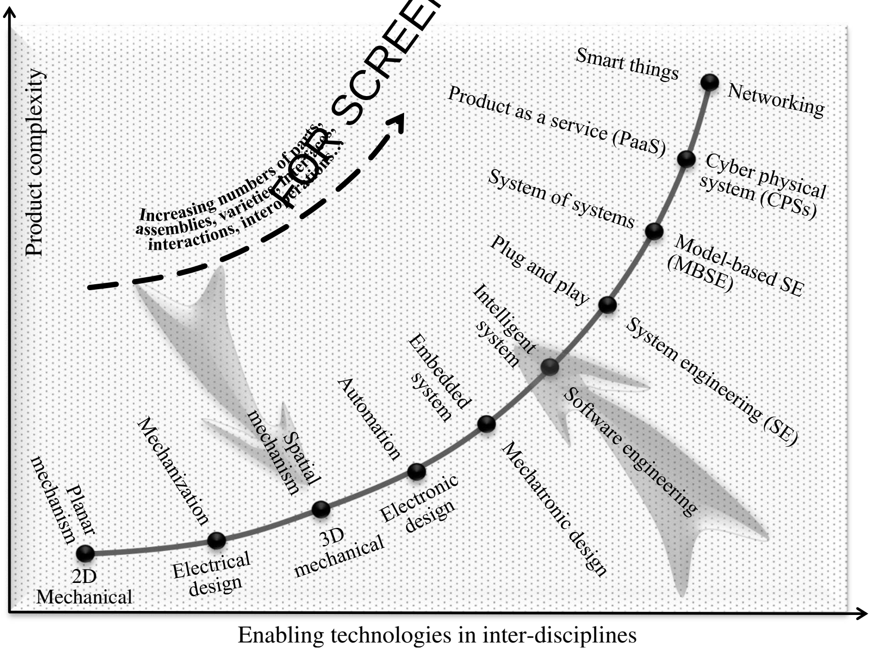


Figure 1.8 Relation of enabling technologies and product complexity

electronics. To make a product smart, electronic and software components play an increasingly important role in sensing internal and external changes, processing data, and controlling the products to respond to the changes adequately. In addition, more and more traditional mechanical components were gradually replaced by electronic or mechatronic systems. For example, a conventional gear transmission in an automobile has been replaced by electronic and software components. In the globalized business environment, enterprises are facing the challenges to increase product diversities with improved efficiency and productivity and the level of customers' satisfaction (Unido 2020).

The progress and the miniaturization we have seen in electronics during the last decades have allowed engineers to come up with new products and new engineering disciplines. Another factor that gives a booming to mechatronics applications is the continuously decreasing prices of electronic parts and the challenges to design very small systems. Taking an example, microprocessors with high performance are becoming very cheap, which encourages their use in computer-controlled systems (Boukas and Al-Sunni 2011). Figure 1.9 shows that enabling ITs has been evolved to support the design and control of complex manufacturing systems with the industry revolution from Industry 1.0 to 4.0.

1) Industry 1.0 was featured by the *mechanization* of manual operations. A machine was purposely constructed to perform tasks on objects. It began with the adoption of water-powered engines in the late 18th century. In over a century, Industry 1.0 had increased six times of average income per capita over the world. Two basic motions of machines were translational and rotational motions that were implemented by basic machine elements such as linkages, gears, cams and cranks, and pulleys and belts. Machine elements changed the speeds or types of motions, so that machinery was not man-powered; therefore, mechanization was synonymous with motorized machines (Wikipedia 2024).
2) Industry 2.0 was featured by e*lectrification* and *electronization* of machines. Electrification and electronization sparked the standardization and industrialization in the late 19th century. Electricity was developed as the new way of generating energy from petroleum; *eletronization* referred to a process or outcome of electronizing for machine controls. Using electric-powered machines to make interchangeable parts, Industry 2.0 made the mass production paradigm

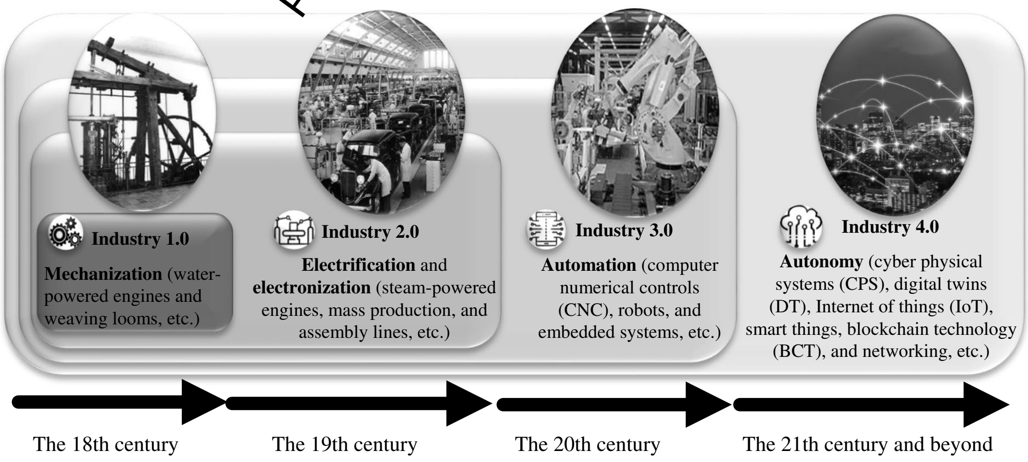


Figure 1.9 From mechanization to autonomy in Industry Revolution (IR)

possible, and this triggered the inventions of cars, airplanes, and telephones, which radically changed people's lives and working styles.

3) Industry 3.0 was featured by the *automation* of products or systems in the early 20th century. Products and systems were automated by the use of *electronics* and ITs. Embedded technologies, microprocessors, and computers were replacing humans' roles in controlling machines and systems; this increased productivity and lowered manufacturing costs. In Industry 3.0, logic processes and ITs were widely used to automate manufacturing processes with less and less human intervention (Venneslan 2009).
4) Industry 4.0 was featured by the *autonomy* of smart systems. Since 2018 with the incorporation of newly developed technologies such as CPS, DT-I, IoT, and *Blockchain Technologies* (BCTs), modern products are expected to become autonomous in the sense that they are capable of (1) sensing the changes and uncertainty in the environment, (2) processing and utilizing sensed data, and (3) reacting at the changes and uncertainties to optimize system objectives autonomously.

Industry 4.0 deals with the increasing levels of complexity, dynamics, uncertainty, distribution, and decentralization. Industry 4.0 is driven by four main factors: (1) the increases of data *Volume, Variety, and Velocity* (3 V); and the capabilities of computing power and networking; (2) the increasing demands of analysis, capabilities, and business intelligence; (3) the needs of the synergies of humans and machines; and (4) the emergence of innovative interactions of digital and physical worlds such as additive manufacturing, digital manufacturing, and robotics. Therefore, Industry 4.0 is characterized by many features linking digitization, optimization, customization, autonomy, adaptation, and human–machine interaction (Wiboqo et al. 2020). Bishop (2002) and Yan et al. (2020) gave a detailed discussion on the impact of emerging technologies on the development of mechatronic systems in Figure 1.10.

1.5 Mechatronic Design Examples

Modern products and systems are mostly mechatronic. Therefore, an engineering design in the real world mostly requires taking into consideration of mechanical, electrical, electronic, and control requirements simultaneously in developing a complete solution to meet the FRs of products. In this section, a few of capstone design projects by the author's students are introduced to show the necessity of using a mechatronic design approach in practice.

1.5.1 Development of Football Robot Team

The design aimed to build a football-playing robot team that would compete in the intercollegiate mechatronic game (Bi et al. 2017). As shown in Figure 1.11, different robots were designed to serve as the roles of a *quarterback*, *receiver*, *center*, or *runner*. These robots must satisfy geometric, weight, and power requirements specified in the regulations and rules of robotic football competitions. Some critical FRs of these robots included that (1) a center robot passed over a football to a quarterback in less than 20 seconds with a success rate higher than 75%; (2) a center, quarterback, or receiver robot was capable of accomplishing a complete pass with a success rate higher than 65%; (3) a receiver robot was capable of traveling 50 ft in 5 seconds, and a central robot was capable of traveling 50 ft in 8 seconds. Moreover, each robot should be able to identify teammates, acquire,

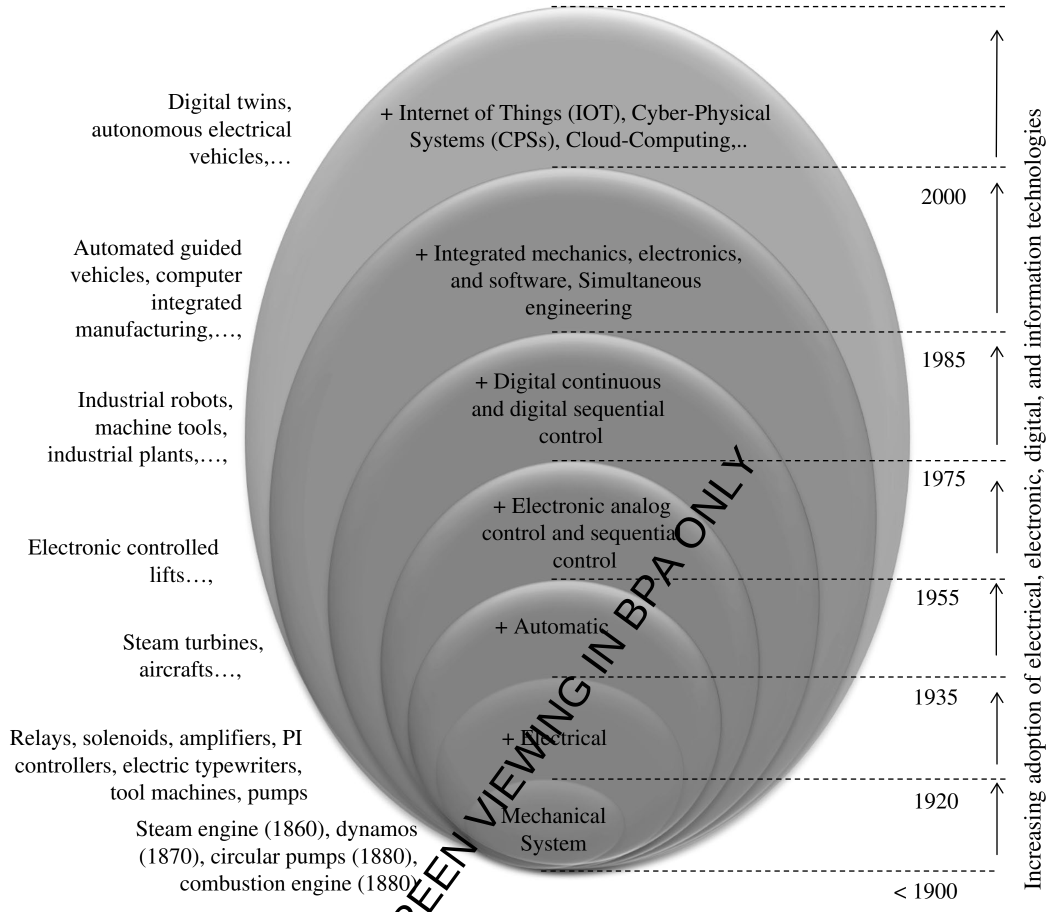


Figure 1.10 Historical development of mechatronic systems

share, and utilize sensed data in a real-time mode, and support its decision-making activities for optimized team performance.

As a system, all of the system elements must be integrated to achieve system-level functions with the desired performance. Figure 1.12 shows that a mechatronic design method is used to (1) decompose system-level FRs into module-level FRs, (2) develop physical solutions to each sub-FRs, and (3) develop the integration solution by which all functional modules are networked, interacted, coordinated, and collaborated to fulfill system-level FRs.

1.5.2 Reusing Robots to Unload Heat Sinks Automatically

The design aimed to adopt a lightweight robot to automate the unloading process of heat sinks at the exit of the heat treatment line (Bi et al. 2015). The expected system requirements include (1) unloading heat sinks without causing damages such as drops, scratches, or dents; (2) placing a part in a box at exits with the positional accuracy of 0.1 in.; (3) achieving a cycle time of operation less than 40 seconds to catch up with the moving speed of the conveyer up to 12.3 in./min; (4) showing the counts of heat sinks in box, alert a supervisor to replace a box, and allow human intervention in operation; and (5) meeting the safety requirements in running the physical system.

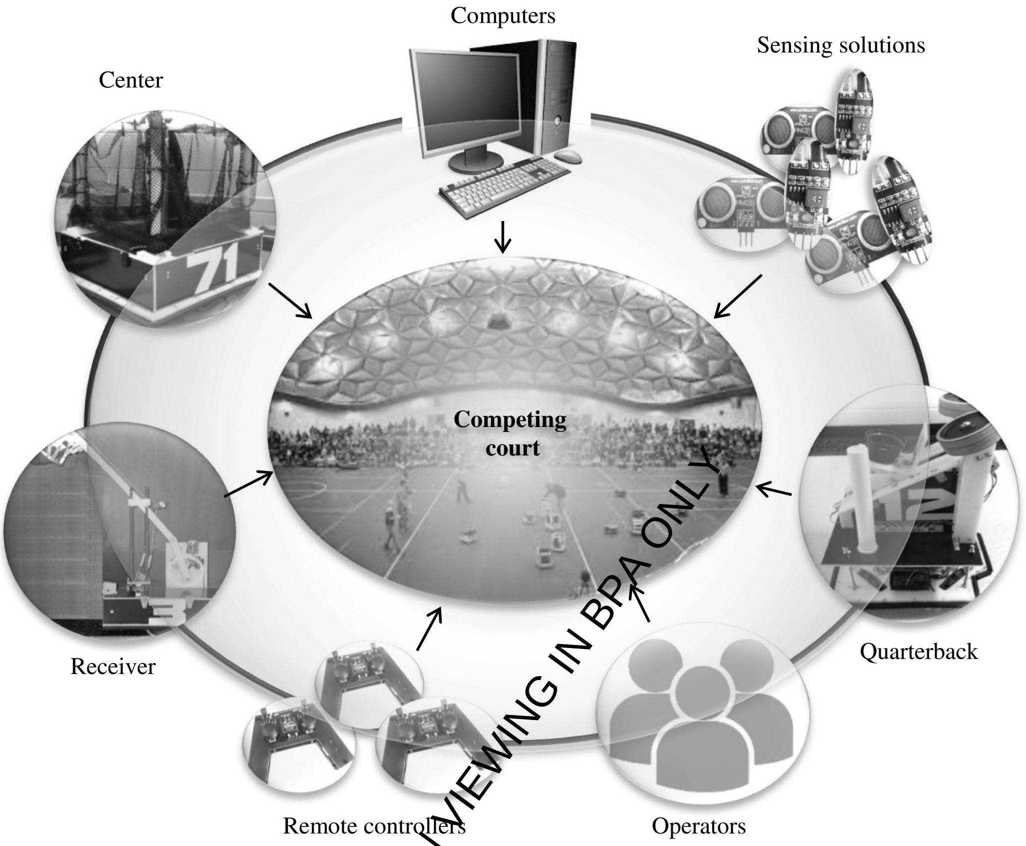


Figure 1.11 Development of robot team for football-playing competition (Bi et al. 2017)

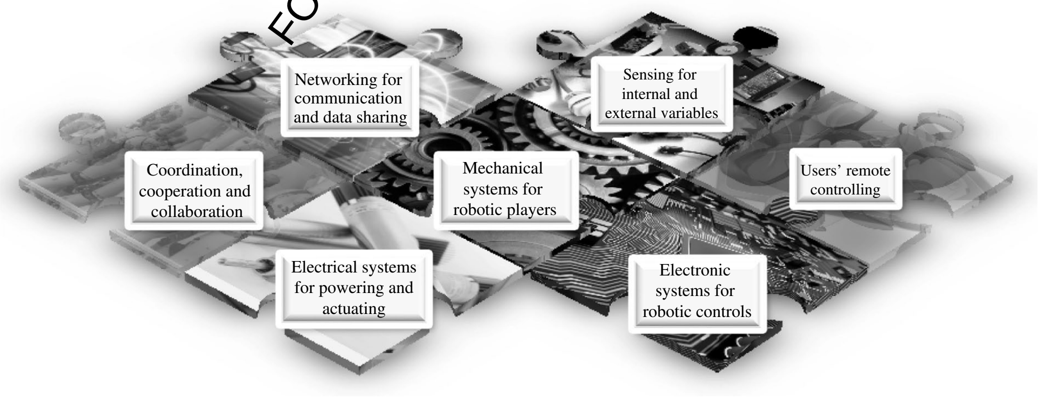


Figure 1.12 Main FRs of designing a football robot team

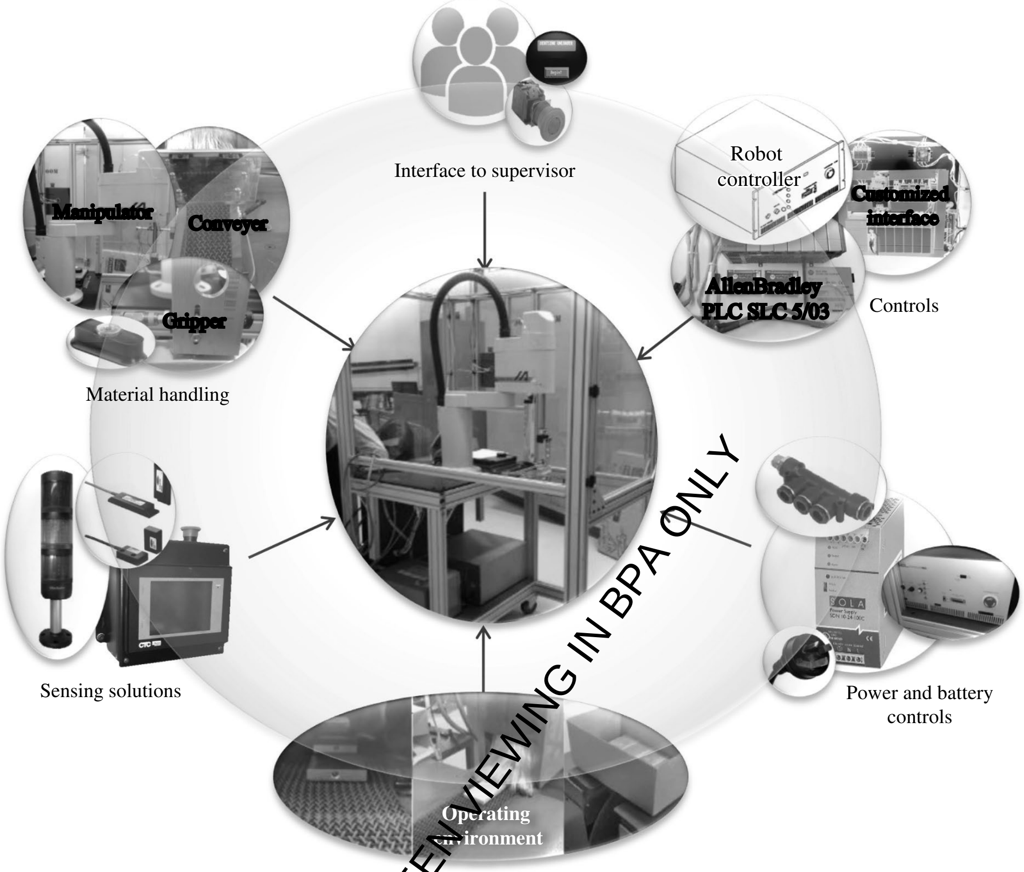


Figure 1.13 Automating heat sink unloading process by a used robot (Bi et al. 2015)

Figure 1.13 shows main categories of system elements, and Figure 1.14 shows that system-level FRs were decomposed into those at the element level as well as their interactions by following mechatronic design principles.

1.5.3 Rebuilding Rail Test Machine

The client company had a test machine to measure the strengths of welds on rails. The hydraulic power system was able to press a specimen with a pressure of up to 300 bar. However, such a capacity must be upgraded since the strengths of upgraded materials can resist up to a pressure of 400 bar. The project aimed to (1) upgrade the hydraulic system with an enhanced loading capacity; (2) reinforce the frame and supports of the test machine for tests with an increased load; (3) develop a user-friendly solution to control a testing process, measure, and visualize a load and corresponding deflection of the specimen over time (Bi et al. 2014a). Figure 1.15 shows five main system elements, that is, mechanical frame, energy absorption, hydraulic power supply, measurement and instrumentation, and testing controls and visualization. Figure 1.16 shows that the system-level FRs were decomposed into four sub-FRs including mechanical support and energy absorption, power supply, sensing system, and testing controlling.

Figure 1.14 Main sub-FRs of automating a heat sink unloading process

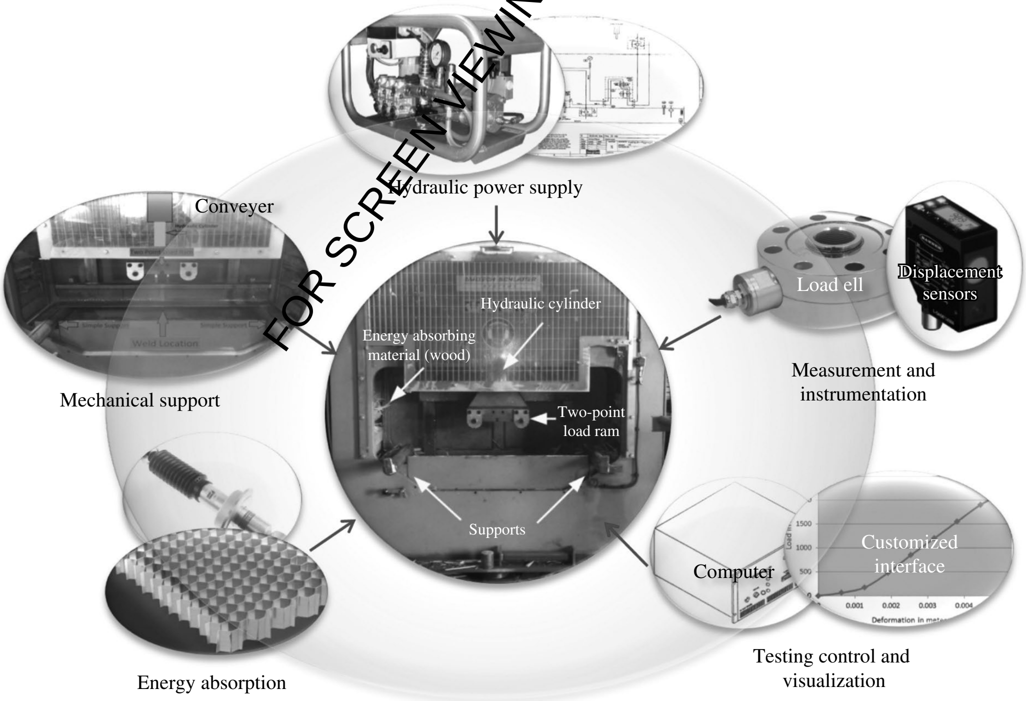


Figure 1.15 Rebuilding a test machine for rails (Bi et al. 2014a)

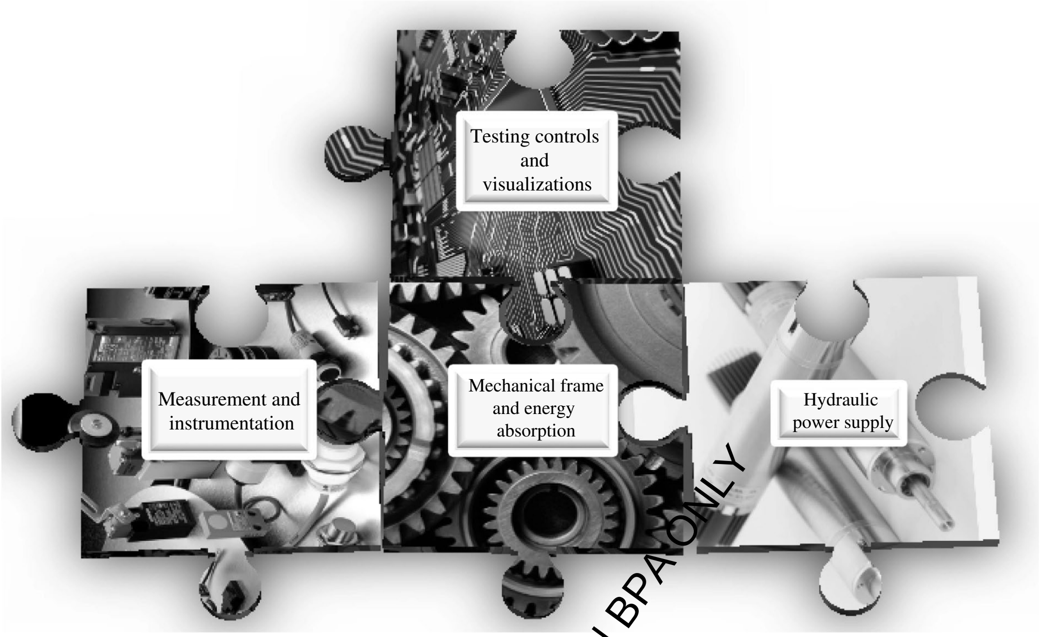


Figure 1.16 Main sub-FRs of rebuilt rail test machine

1.5.4 Testing of Electric Hardness

The client company made customized cable harnesses for home appliances. The quality of its cable harnesses was guaranteed by functional tests on randomly selected products. However, manual testing involved intensive labor and relied heavily on subjective judgments. The project aimed to develop a semi-automated workstation to (1) reduce the manual effort in setting up cable harnesses and mapping input and output ports and (2) eliminate the possibility of undetected defects. The main requirements for the testing workstation were to (1) detect both open and crossed connections, (2) assist testers without special training, (3) have a cycle time of less than 20 seconds for same type of cable hardness, (4) have a changeover time for different types of cable hardness of less than 5 minutes, and (5) be capable of testing over 20 different types of cable hardness and expandable for more types with customized adaptors (Bi et al. 2018). Figure 1.17 shows that a modularized architecture is used, the system-level FRs are decomposed into five module-level sub-FRs that are fulfilled by corresponding physical solutions. The five main modules were mechanical interface, electronic interface, power supply, testing control, and interface to the operator.

1.5.5 Valve Needle Assembly Station

As shown in Figure 1.18a, valves were critical components to implement the control of a pneumatic actuator. A valve was assembled from a needle, an O-ring, and a screw retainer in two steps as shown in Figure 1.18b, that is, (1) a pressing process to place the R-ring in the slot of the needle and (2) a threading process to thread the screw at the end of the needle. Both these processes were performed manually, and an operator easily felt vision or muscle fatigue due to the small sizes of parts at a scale of millimeters.

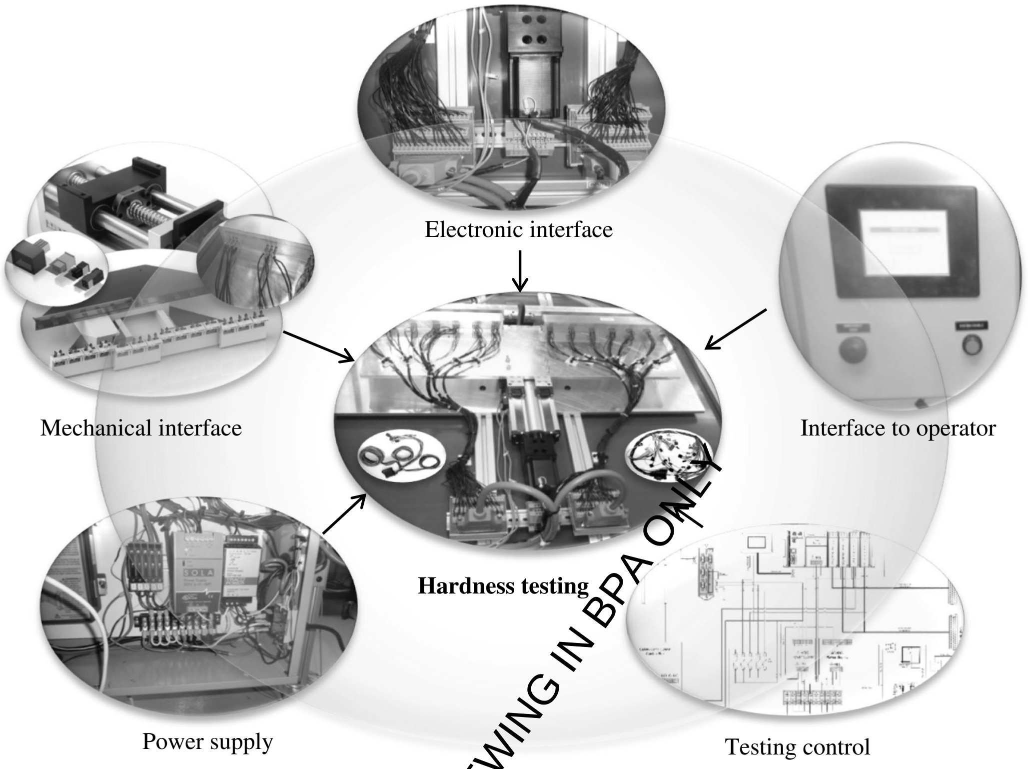
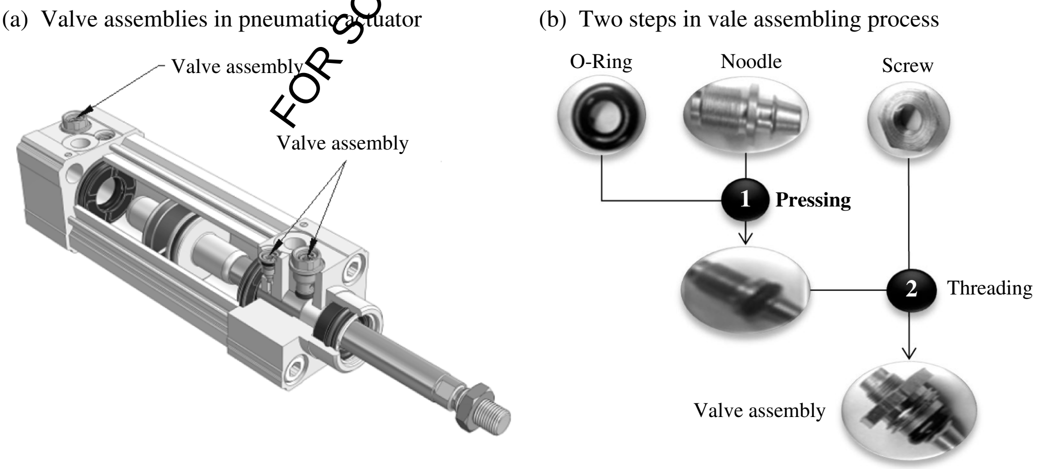


Figure 1.17 Main modules of a semi-automated cable hardness testing workstation (*Source:* Bi et al. (2018)/ MDPI/CC BY 4.0)


(a) Valve assemblies in pneumatic actuator

(b) Two steps in vale assembling process

Figure 1.18 Assembly of flow control valve

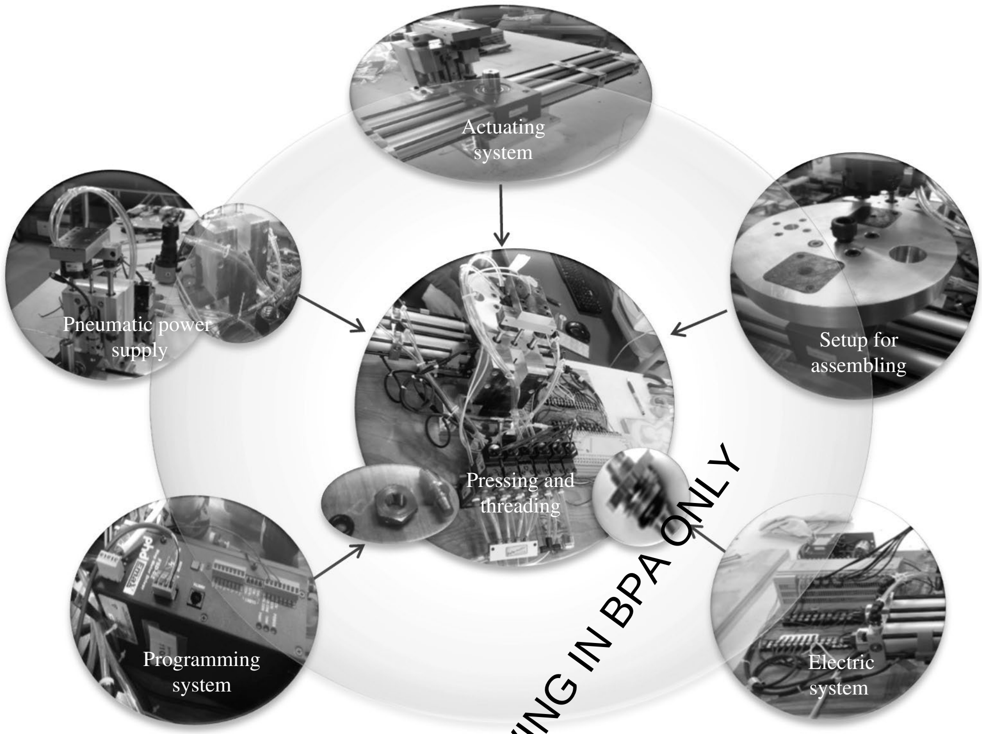


Figure 1.19 Mechatronic design of semi-automated valve assembly workstation

The client requested to develop an assistive workstation where parts were placed manually at given locations and the pressing and threading processes were automated. The semi-automated system was required to produce one valve in less than five seconds, one setup for a batch of at least 1000 valves, and no manual intervention except for (a) feeding parts and (b) emergency stops. Figure 1.19 shows the mechatronic design of the semi-automated valve assembly works. The system-level FRs were decomposed into five sub-FRs, which were fulfilled by five systems, respectively. These five subsystems were (1) an actuating system for all required movements in two assembling tasks, (2) a setup system to position and orientate parts in fixtures, (3) an electric system for the interactions of mechanical and actuating systems, (4) a programming system for system control, and (5) a pneumatic power system to regulate power supply for system operation.

1.5.6 Ejecting Engine Fans from Performance Tester

The specifications of engine fans were measured by having performance tests for products randomly selected from a production line. The client company had a workstation to test engine fans. However, it ran into a number of technical issues that led to uncertain downtimes in a product line. In the existing system, a fan was lifted by a pair of parallel rails and was conveyed and ejected out on top of thin round belts to a mating conveyor, then further transported outside the product line by inertia force. Parts were easily damaged in the lifting process and the duration of the transition from one location to another, and fixtures were quickly worn or damaged due to improper changeovers.

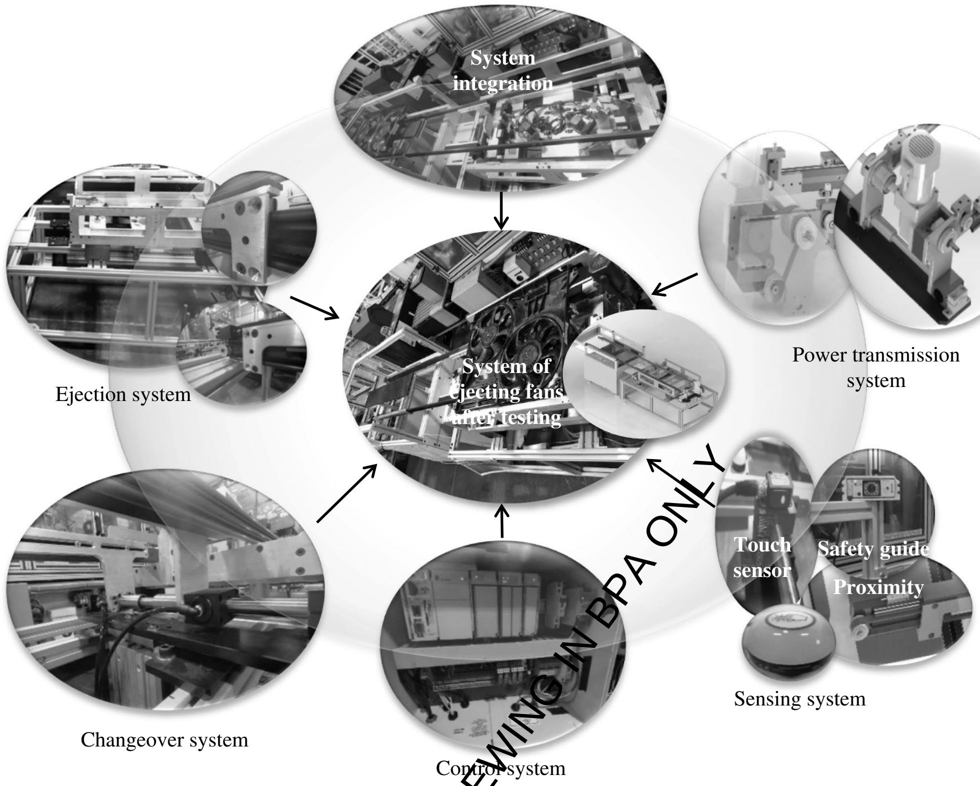


Figure 1.20 Six subsystems of the new engine fan ejection system

The project aimed to develop a new ejection system to meet the requirements of (1) automating fan-ejection process without any damage to fans, (2) being applicable to a variety of engine fans of up to 20 lb for both single- and dual-fan assemblies, (3) ejecting a fan in less than 3.5 cycle time, (4) being integrated with existing CompactLogix PLC, and (5) meeting system safety and reliability standards. Figure 1.20 shows the mechatronic design of a new fan ejection system. The system-level FRs were decomposed into six sub-FRs, which were fulfilled by six systems, respectively. These six subsystems were (1) a new ejection mechanism to lift and transfer a tested fan from the testing workstation to outside of product line in less than 3.5 seconds, (2) a changeover system, especially dealing with two identified technical issues, (3) a power transmission system to provide power for all moving components, (4) the sensing system that acquires the data of motion variables for closed – loop system controls, (5) a control system that uses sensed data to operate fan testing workstation, and (6) an integration system to connect all sub-systems seamlessly.

1.5.7 Demonstrator of Automated Spacer Removals in Truck Assembly Line

The client company produced 0.5–1 ton trucks at a rate of one truck per minute. The first step of a truck assembly line was to place the truck chassis at its entrance, and one essential task was to remove frame spacers from the chassis. Frame spacers were placed among the chassis so that individual chassis were protected and transported in stacked structures. When a chassis was placed on the assembly line, up to four frame spacers must be detected and removed from the chassis, and these operations were performed manually.

The company requested to explore the technical feasibility of automating the detection and removal of frame spacers from the chassis at this workstation. The automation was required to (1) locate spacers; (2) lift, remove, and transport spacers one by one to storage at the specified location; and (3) alert the operator for a manual operation if a spacer was sticking or at an abnormal position. If the system fails to remove a spacer, an alert must be sent to an operator for manual spacer removal. The automated system would be evaluated on the success rate of removing the spacers and its reaction to failure. With these specifications in mind, the mechatronic design focused on a spacer removal mechanism and a control system in order to achieve a working prototype.

Figure 1.21 shows the mechatronic design of the spacer removal demonstrator. The system-level FRs were decomposed into five sub-FRs that were fulfilled by five sub-systems, respectively. These subsystems were (1) a magnetic manipulator to pick spacers from truck frames and move them to specified containers; (2) a gantry support system to move the manipulator in a three-dimensional space; (3) the subsystem of power supplies for electric and pneumatic actuators and control systems; (4) the subsystem of all sensing solutions to identify spacers and humans, and detect the positions of actuators for closed loop controls; (5) the control system that connected all system elements as an integrated system and operated the system based on operators' inputs and real-time data acquired from the subsystem of sensing solutions.

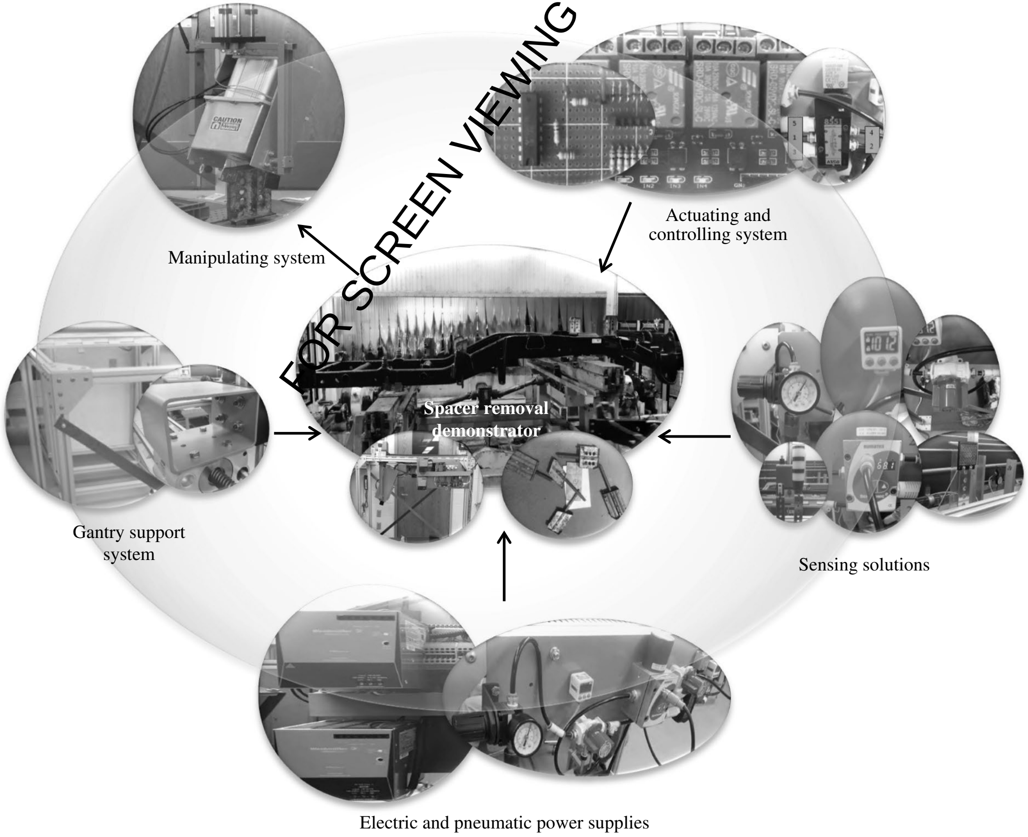


Figure 1.21 Subsystems of a spacer removal demonstrator

1.6 Group Technologies (GTs) for Mechatronic Designs

The complexity of a product or system can be measured by a *Shannon entropy* that was initially introduced to quantify the amount of energy in thermodynamics; it was then used to measure the randomness and disorders of the system as (Isik 2010; Vrabič and Butala 2012; Sönmez and Koç 2015; Fredendall and Gabriel 2019),

$$H(\chi) = \sum_{x \in \chi} p(x) \cdot \log_2 \left(\frac{1}{p(x)} \right) \tag{1.1}$$

where $H(\chi)$ is the system entropy for the amount of information relating to randomness and uncertainties of the interactions of system elements. χ is the set of possible events, that is, interactions of system elements. $p(x)$ is the probability of the occurring event $x \in \chi$. $\log_2$ is the function to normalize probability into "0" or "1."

Equation (1.1) shows that the entropy depends on two factors: (1) the number of possible events χ and (2) the probability $p(x)$ when event $x \in \chi$ occurs. Moreover, the entropy decreases when (1) the number of possible events decreases and (2) the probability $p(x)$ of an event $x \in \chi$ becomes more certain.

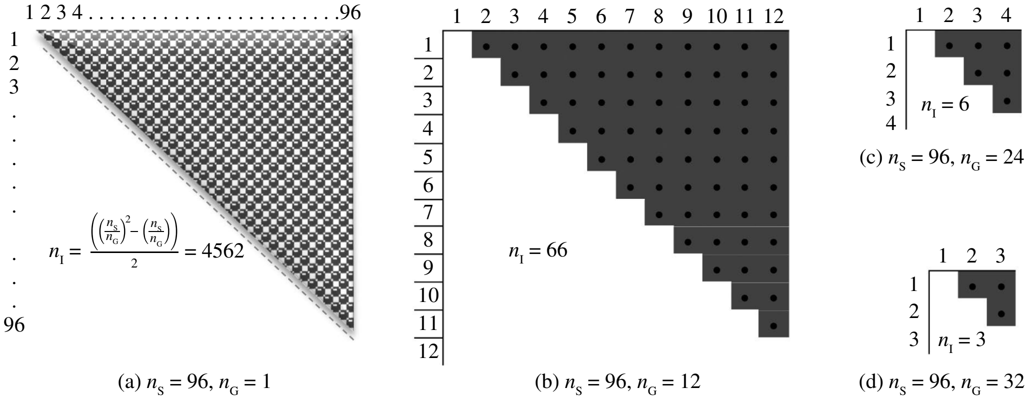
Since the number of possible events depends on the number of interactions among system elements, grouping system elements into components and sub-systems will reduce system complexity significantly (Bi et al. 2021b, 2021c). Taking an example of a system with a total number (n_S) of FRs is $(3 \times 4 \times 8) = 96$, if DSs would be defined by these FRs, respectively.

When one DS can satisfy one FR, that is, the number of FRs that are satisfied by one DS (n_G) is 1; then, the total number (n_I) of possible interactions among system elements becomes,

$$n_I = \left[\left(\frac{n_S}{n_G} \right)^2 - \left(\frac{n_S}{n_G} \right) \right] / 2 \tag{1.2}$$

where $\left(\frac{n_S}{n_G} \right)$ is the number of groups in the system.

As shown in Figure 1.22, when the number (n_G) of the satisfied FRs in each DS is set as 1, 3, 4, 6, 12, 24, 32, and 48, respectively, Eq. (1.2) determines the corresponding number of system interactions as 4560, 496, 276, 120, 66, 6, 3, and 1, respectively.



(a) $n_S = 96, n_G = 1$ (b) $n_S = 96, n_G = 12$ (c) $n_S = 96, n_G = 24$ (d) $n_S = 96, n_G = 32$

Figure 1.22 Decrease of system complexity (n_I) with an increase of group size (n_G)

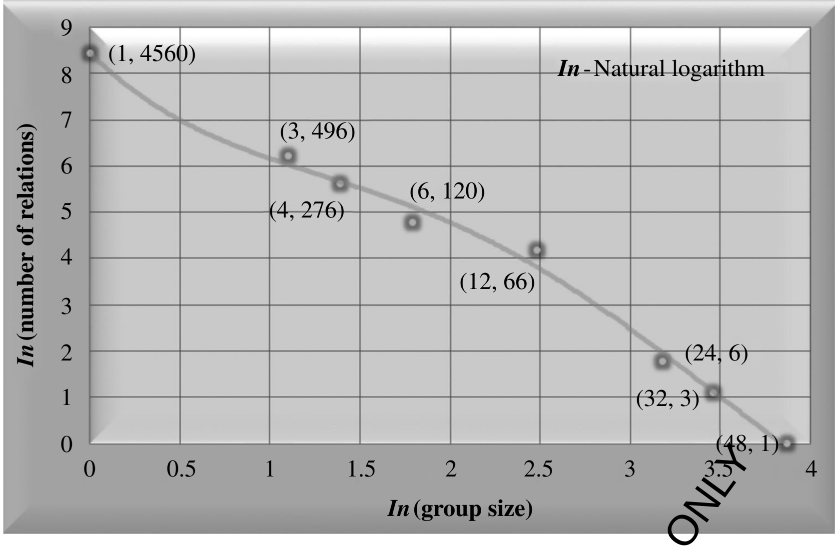


Figure 1.23 Example of the impact of group size on system complexity when the number of basic system elements is $n_s = (3 \times 4 \times 8) = 96$

Figure 1.23 shows that system complexity (n_I) is reduced monotonically with an increase of granularity (n_G) in a grouping.

Engineered products usually consist of components from different disciplines. Products can be developed in different ways that can be classified into three categories as shown in Figure 1.24. First, traditionally, *a sequential design process* is used to take into consideration of design constraints and optimization discipline by discipline. A high cost occurs due to the need of iterations for redesigning and retooling. Second, *disciplinary-specific concurrent designs*, such as DfA and DfM, are used to take into consideration of design constraints and optimizations in two or a few disciplines. Third, *mechatronic design* is used to take into consideration of all constraints and system-level objectives simultaneously. Traditional engineering disciplines, such as mechanical, electrical, chemical, and civil engineering, were developed in the 20th century; they have respective bodies of theories, knowledge, methodologies, and design tools in mutually exclusive intellectual and professional territories (Alciatore 2019).

1.7 Mechatronics and Mechatronic Functional Modules (MFMs)

The discussion in Section 1.6 shows that the effectiveness of mechatronic design in dealing with system complexity depends on the identification of grouped DSs for corresponding FRs. *The higher* the level of grouping applied, *the more* the number of system interactions can be reduced; *the closer* the relevance of grouped DSs are, and *the easier* and *the more* meaningful grouped DSs can be integrated as sub-systems.

Following the mechatronic designing procedure, a mechatronic system is integrated from a set of mechatronic functional modules (MFMs). In this book, *an* MFM refers to a DS to satisfy one or a set of system FRs. Depending on specified FRs, an MFM can be a collective and integrated solution of

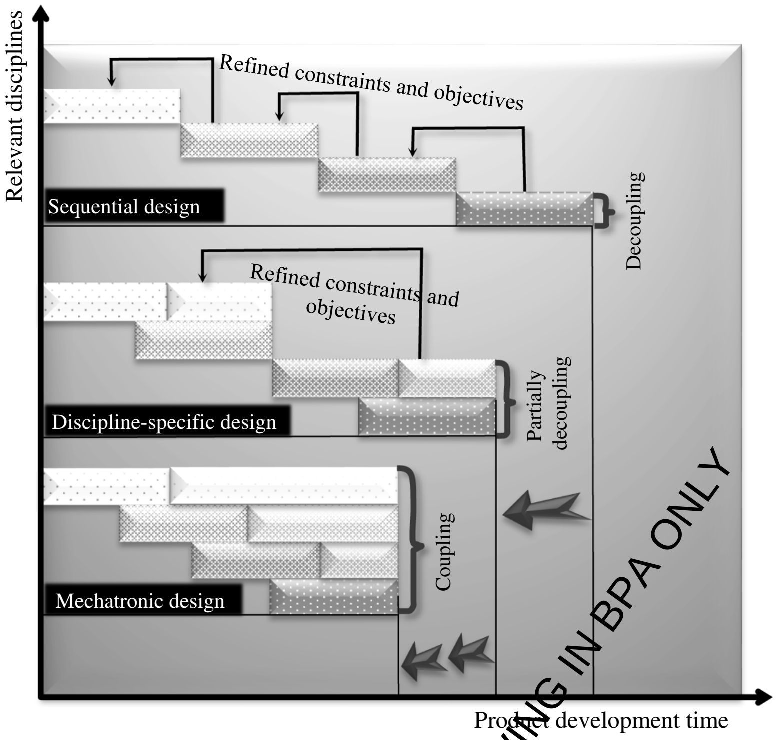


Figure 1.24 Differences among mechatronic, discipline-specific, and sequential designs

mechanical, electric, electronic, and control solutions. An MFM can also be an integration of a set of low-level MFMs.

Mechatronics, also called mechatronics engineering, is an interdisciplinary branch of engineering that focuses on the engineering of electronic, electrical, and mechanical engineering systems. In regard to relevant disciplines, mechatronics also closely relates to robotics, electronics, computers, telecommunications, systems, control, and product engineering. Note that mechatronics was originally intended to be nothing more than a combination of mechanics and electronics; hence, the name being a portmanteau of mechanics and electronics; however, as the complexity of technical systems continued to evolve, the definition had been broadened to include more technical areas (Wikipedia 2024) (Figure 1.25).

Figure 1.26 provides an external view of a product-oriented mechatronic system and its boundaries. Alongside the actual mechatronic system (the product), two additional important, interacting agents can be seen: the *user* and the *environment*. The rationale behind a mechatronic product was its *user-based purpose*. A mechatronic system never existed for its own sake; instead, it was designed to interact with users and environment through *man–machine interface*. In the simplest case, this consisted of a start button to enable a complex task that would be carried out by the mechatronic system automatically.

Figure 1.27 illustrates a mechatronic system from the structural perspective. A mechatronic system was used to replace or expand humans' abilities in (1) sensing environments; (2) performing tasks; (3) making decisions to respond to changes; and (4) performing comprehensive tasks with data collection, processes, and utilization for decision-making and execution.

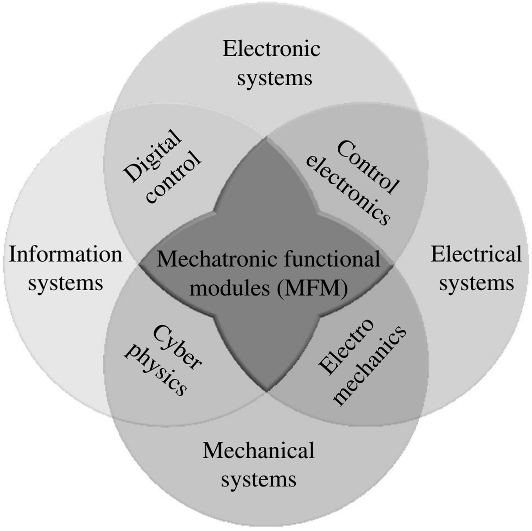


Figure 1.25 Integrated mechatronic system (*Source:* Craig and Stolfi (2002)/with permission of Elsevier)

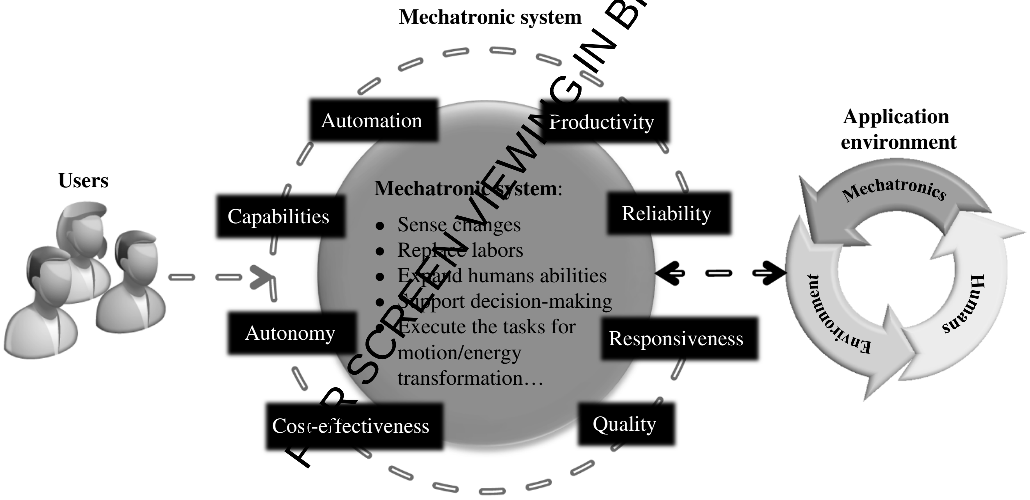


Figure 1.26 Mechatronic system from users' perspective

1.8 Mechatronic Design Methodologies

Mechatronic products and systems are not new. On the one hand, most of the engineered products are integrated mechanical, electrical, and information systems; on the other hand, these integrated products are not necessarily developed by engineers who have been trained for multidisciplinary designs. However, learning mechatronics helps engineers greatly to perform an effective and efficient process in defining, classifying, organizing, and integrating disciplinary solutions into a system-level solution. From this perspective, mechatronics should be taught more on *mechatronic design methodologies* rather than *mechatronics* itself; in addition, the scope of mechatronics has been broadened gradually over the years.

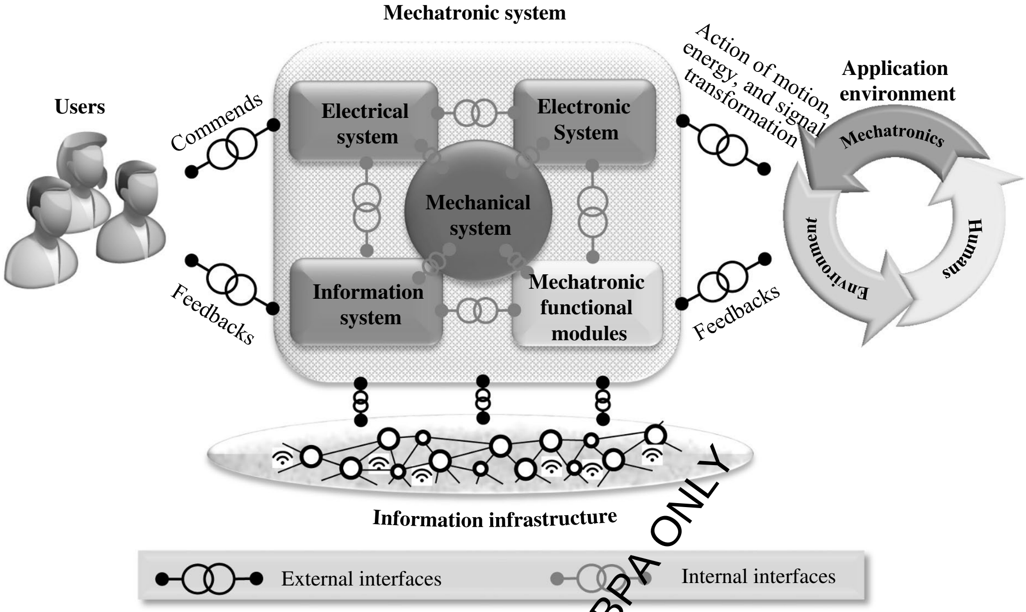


Figure 1.27 Mechatronic system from a structural perspective

Mechatronics is *a philosophy* that reflects the advance of human civilization in interdisciplinary science. Designers in any engineering discipline can benefit greatly by setting their minds on the synthesis of interdisciplinary knowledge to meet emerging engineering challenges. In fact, the concept of mechatronics itself came from the evolution of engineering design methodologies. These design methodologies have been integrated to advance mechatronic products by adopting more and more embedded components, computing resources, and ITs. Moreover, rapidly developed DT-I, CPSs, *bio-electro-mechanical systems*, *quantum computing*, *micro-electronic-mechanical systems* (MEMS), and *nanotechnologies* have brought new growth points of traditional mechatronics (Yan et al. 2020).

In the next chapter, mechatronic systems will be analyzed to identify more important characteristics such as modularity, integrability, coupling disciplines, concurrent deigns, decentralized controls, event-driven automations, adaptability, predictability, resilience, and continuous adaptation. Therefore, a mechatronic design process must be needs-driven, and different design methodologies such as *model-based system engineering* (MBSE), a*xiomatic design theory* (ADT), *unified modeling language* (UML), *concurrent design optimization* (CDO), and *virtual verification and validation* (VVV) should be utilized to satisfy the FRs of mechatronic designs at a different phase. Finally, *the project-based mechatronic design* (PBMD) will be introduced as a platform to integrate all available computer-aided tools as long as they add values to the mechatronic system to be designed.

1.9 Organization of the Book

In this book, PBMD is introduced as a methodological framework to integrate a number of multidisciplinary design methods to support needs-driven designs of *Mechatronics*, CPSs, IoT, *Human Cyber Physical Systems* (HCPSs), and beyond. This book aims to provide an alternative book on mechatronics with the improvement on (1) the theoretical foundation of mechatronics; (2) the methodological framework to enable needs-driven designs of complex products or systems; and (3) the evolution of mechatronics to embrace emerging technologies including DT-I, CPSs, IoT, and Metaverse in the digital era.

The book is organized comprehensively to achieve the following objectives: (1) generalize the concept of a mechatronic system as an integrated solution by assembling and interacting a set of *static* and *dynamic*, *sole-disciplinary* and *multidisciplinary*, and *virtual* or *physical* functional modules that add values to systems in their own ways. Students are educated mainly on how to interpret customers' needs into system-level FRs, decompose high-level FRs into low-level sub-FRs, and finally select the right functional modules to meet sub-FRs, respectively. Knowledge, experience, and skills to design and implement functional modules are secondary. (2) Discuss mainstream multidisciplinary design methods including MBSE, CDO, ADT, and VVV with an emphasis on their roles in creating the innovations of mechatronic systems. (3) Emphasize the innovations of a mechatronic product on selection, integration, coordination, collaboration, and cooperation of MFMs to achieve system-level objectives rather than innovations on individual MFMs. (4) Develop a methodological framework for students to utilize appropriate multidisciplinary methods at different developmental phases of mechatronic products. (5) Broaden mechatronics to cover the most relevant and influential technologies including DT-I, DT-II, CPSs, human–robot interactions (HRIs), HCPSs, IoT, CC, BCT, and Metaverses.

Figure 1.28 shows the organization of the book. Chapter 1 gives an overview of the historical development of Mechatronics and discusses the need to teach mechatronic design methodologies rather than mechatronics itself. Chapter 2 introduces the common ways for innovations to characterize mechatronic systems from the design perspective, commonly used multidisciplinary design methodologies are discussed to explore their roles in creating innovations in mechatronic systems, and PBMD is presented as the methodological framework to integrate various multidisciplinary design methodologies for needs-driven designs. Chapters 3–8 discuss the designs of MFMs in power supplies, actuating, sensing, signal processing, cyber systems, and control systems. Chapters 9–15 introduce emerging technologies in the recent development of mechatronics including DT-Is, CPSs, IoT, Robotics, end-effector tools, Metaverse, and HRIs.

1.10 Summary

Since its birth, mechatronics has continuously evolved to deal with multidisciplinary designs with the ever-increasing complexity. Classic books focus on mechatronics itself and underestimate its importance as a design philosophy. There is a need to provide some alternatives in teaching mechatronic courses with two primary purposes to (1) understand mechatronic design methodologies and (2) incorporate newly developed technologies in mechatronics.

PBMD is proposed as a methodological framework to integrate various multidisciplinary methodologies to create innovations in mechatronic systems at different levels and aspects. The proposed book is expected to fill the gap of mechatronic educations with its features of (1) classifying innovations and converting these into FRs of mechatronic systems; (2) presenting PBMD as a methodological framework to integrate system modelling language (SysML), ADT, MBSE, CDO, and VVV in mechatronic design; (3) generalizing single or multidisciplinary system components as MFMs; (4) embracing emerging technologies DT-I, CPSs, Metaverse, HRIs, and HCPSs in mechatronics.

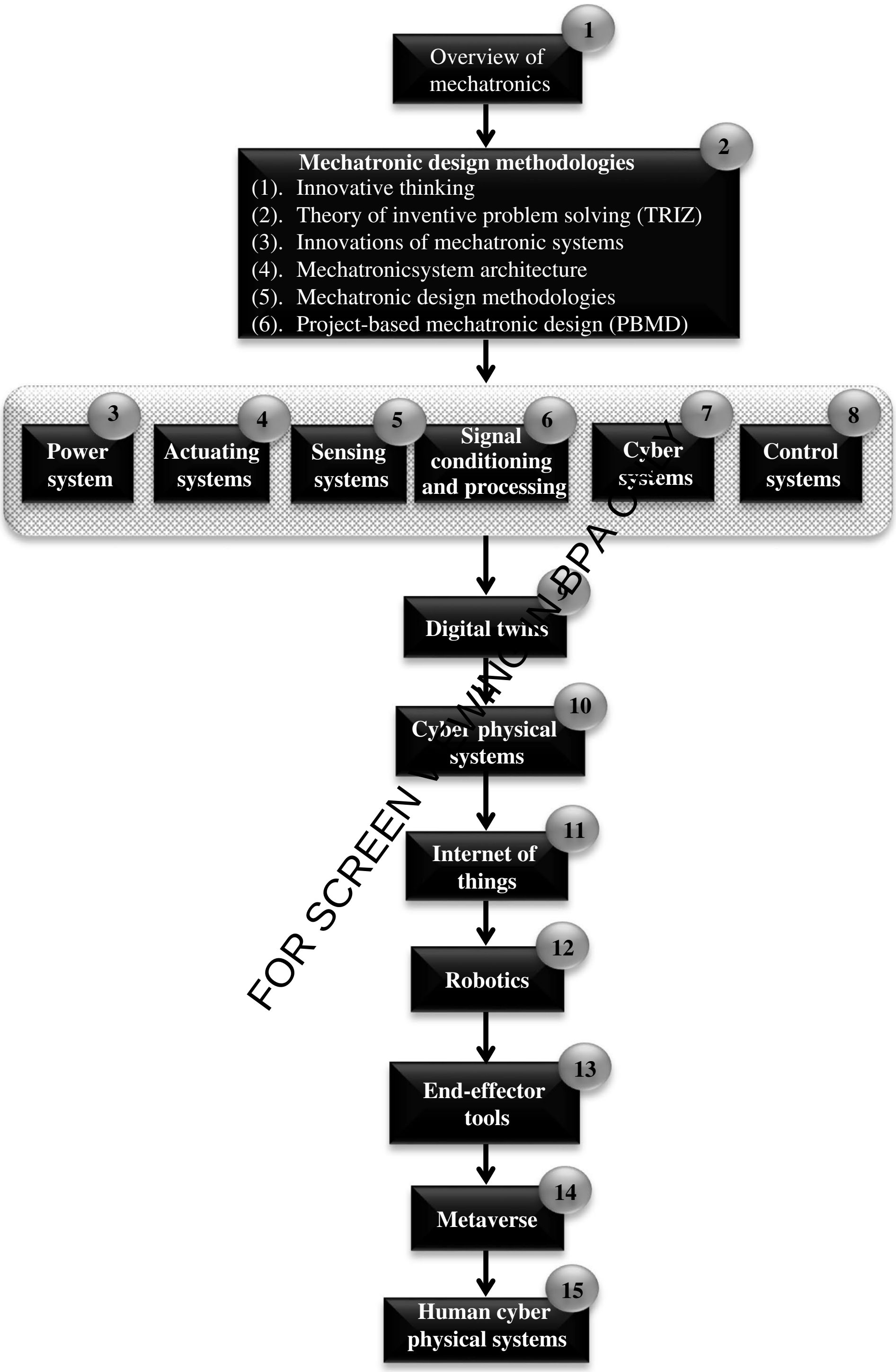


Figure 1.28 Organization of book

Problems

1.1 What are the basic functional requirements (FRs) of a mechatronic system? Give a few real-life examples to support your answers.

1.2 What are some essential components of a mechatronic system? Give a few real-life examples to support your answers.

1.3 What are your criteria to justify if a product or system is a mechatronic system? Use your criteria to justify if an industrial robot is a mechatronic system.

1.4 What are your criteria to justify if a product or system is a mechatronic system? Use your criteria to justify if any of the following products is a mechatronic system: (1) a mechanical watch, (2) a smartwatch, (3) a mercury thermometer, (4) an LED light, (5) a smartphone, (6) an app, (7) a microwave, and (8) a programmable logical controller.

1.5 What are the differences between an "integral" system and a "modular" system? Compare advantages and disadvantages of integral and modular systems with examples.

1.6 What are the differences between a "sequential" design and a "concurrent" design? Compare the advantages and the disadvantages of sequential and concurrent designs with examples.

1.7 What is a needs-driven design? Why is it important in mechatronic design?

1.8 How to measure the complexity of a system?

1.9 How does the number of system elements affect system complexity?

1.10 How does the number of system interactions affect system complexity?

1.11 How can mechatronic designs deal with system complexity effectively?

References

Adamsson, N. (2005). Mechatronics engineering: new requirements on cross-functional integration. Licentiate thesis. ISSN 1400-1179. KTH Royal Institute of Technology S-100 44 Stockholm, Sweden.

Adamsson, N. (2007). Interdisciplinary integration in complex product development – managerial implications of embedding software in manufactured goods. Doctoral thesis. Royal Institute of Technology, ISBN 978-91-7178-610-4.

AIMSek (2024). How does PLM help in managing next-generation complexity. https://www.aimdek.com/blogs/plm-help-managing-next-generation-product-complexity (accessed 12 September 2024).

Alciatore, D.G. (2019). *Introduction to Mechatronics and Measurement Systems*, 5e. McGraw-Hill Education.

Alkan, B., Vera, D.A., Ahmad, M. et al. (2018). Complexity in manufacturing systems and is measures: a literature review. *European Journal of Industrial Engineering* 12 (1): 116–150.

Babanli, M.V., Prima, F., Vermaut, P., et al. (2019). Review on the new materials design methods. https://link.springer.com/chapter/10.1007/978-3-030-04164-9_124 (accessed 12 September 2024).

den Beemt, A.V., MacLeod, M., der Veen, J.V. et al. (2020). Interdisciplinary engineering education: a review of vision, teaching, and support. *Journal of Engineering Education* 109: 508–555.

BeyondPLM (2018). Achilles heel of MBSE and PLM modeling. http://beyondplm.com/2018/08/14/achilles-heel-mbse-plm-modeling (accessed 12 September 2024).

Bi, Z.M. (2002). On adaptive robot systems for manufacturing applications. Doctoral thesis. University of Saskatchewan, Canada. https://harvest.usask.ca/handle/10388/etd-07302008-094853 (accessed 12 September 2024).

Bi, Z.M. (2011). Revisiting system paradigms from the viewpoint of manufacturing sustainability. *Journal of Sustainability* 3 (9): 1323–1340.

Bi, Z.M. and Wang, X.Q. (2020). *Computer Aided Design and Manufacturing*, 2020. Hoboken, NJ: Wiley-ASME Press Series.

Bi, Z.M., Pomalaza-Raez, C., Singh, Z. et al. (2014a). Reconfiguring machines to achieve system adaptability and sustainability: a practical case study. *The Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 228: 1676–1688.

Bi, Z.M., Xu, L.D., and Wang, C. (2014b). Internet of things for enterprise systems of modern manufacturing. *IEEE Transactions on Industrial Informatics* 10 (2): 1537–1546.

Bi, Z.M., Yanfei, L., Baumgartner, B. et al. (2015). Reusing industrial robots to achieve sustainability in small and medium-sized enterprises (SMEs). *Industrial Robot* 42 (3): 264–273.

Bi, Z.M., Wang, G., Xu, L.D. et al. (2017). Witte C and Sidwell C (2017) IoT-based system for communication and coordination of football robot team. *Internet Research* 27 (3): 162–181.

Bi, Z.M., Pomalaza-Raez, C., Hershberger, D. et al. (2018). Automation of electrical cable harnesses testing. *Robotics* 7 (1): https://doi.org/10.3390/robotics7010001.

Bi, Z.M., Jin, Y., Maropoulos, P. et al. (2021a). Internet of things (IoT) and big data analytics (BDA) for digital manufacturing (DM). *International Journal of Production Research* https://doi.org/10.1080/00207543.2021.1953181.

Bi, Z.M., Zhang, W.J., Wu, C. et al. (2021b). Generic design methodology for smart manufacturing systems from a practical perspective, part I – digital triad concept and its application as a system reference model. *Machines* 9 (10): 207.

Bi, Z.M., Zhang, W.J., Wu, C. et al. (2021c). Generic design methodology for smart manufacturing systems from a practical perspective, part II – systematic designs of smart manufacturing systems. *Machines* 9 (10): 208.

Bishop, R.H. (2002). The mechatronics handbook, ISA-The Instrumentation Systems, https://www.cic.ipn.mx/~pescamilla/SensAct/Bishop2002.pdf (accessed 12 September 2024).

Boukas, E.K. and Al-Sunni, F.M. (2011). *Mechatronic Systems – Analysis, Design and Implementation*. Springer.

Craig, K. and Stolfi, F. (2002). Teaching control system through mechatronics: academic and industrial perspectives. *Mechatronics* 12 (2): 371–381.

DE247 (2024). By the number: product complexity. https://www.digitalengineering247.com/article/by-the-numbers-product-complexity (accessed 12 September 2024).

Defoort, S., Balesdent, M., Klotz, P. et al. (2012). Multidisciplinary aerospace system design: principles, issues, and onera experience. *Multidisciplinary Aerospace System Design* 2012 4: 1–15.

Featherston, C. and O'Sullivan, E. (2014). A review of international sector strategies and roadmaps: a case study in advanced materials. https://www.ifm.eng.cam.ac.uk/uploads/Resources/Featherston__OSullivan_2014_-_A_review_of_international_public_sector_roadmaps-_advanced_materials_full_report.pdf (accessed 12 September 2024).

Fredendall, L.D. and Gabriel, T.J. (2019). Manufacturing complexity: a quantitative measure, https://pdfs.semanticscholar.org/39c5/b53dd70414acae58532a0a8010193af221d3.pdf (accessed 12 September 2024).

GeneralPlastics (2021). Composite core: factors to consider when choosing core material for your application. https://www.generalplastics.com/technical-papers/composite-core-factors-to-consider-when-choosing-core-material-for-your-application (accessed 12 September 2024).

Grant, P. (2013). New and advanced materials. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/283886/ep10-new-and-advanced-materials.pdf (accessed 12 September 2024).

Groover, M.P. (2020). *Fundamentals of Modern Manufacturing: Materials, Processes and Systems*, 7e. Wiley.

Hutagalung, S.D. (2012). *Materials Science and Technology*. Rijeka, Croatia: InTech.

Isik, F. (2010). An entropy-based approach for measuring complexity in supply chains. *International Journal of Production Research*, 2010 48 (12): 3681–3696.

Orfi, N., Termpenny, J., and Sahin-Sariisik, A. (2011). Harnessing product complexity: step 1 – establishing product complexity dimensions and indicators. *The Engineering Economist* 51 (1): 59–79.

van der Roest, D. (2017). Empowering quoting and program execution for automotive suppliers. https://www.vdr.com/the-practical-plm-blog/2017/fueling-new-business-effective-execution-for-automotive-suppliers-part-1-of-3 (accessed 12 September 2024).

Rowe, J. (2019). Managing product complexity, regulations and requirements. https://www.engineering.com/DesignSoftware/DesignSoftwareArticles/ArticleID/18471/Managing-Product-Complexity-Regulations-and-Requirements.aspx (accessed 12 September 2024).

Sönmez, O.E. and Koç, V.T. (2015). On quantifying manufacturing flexibility: an entropy based approach. *Proceedings of the World Congress on Engineering 2015 Vol II WCE 2015*, London, UK (1–3 July 2015).

Strong, D.S. (2021). Towards effective multidisciplinary engineering education: the multidisciplinary design stream at Queen's university. https://pdfs.semanticscholar.org/a6b2/e9c04f6d3e378391e24f5f46a91ea483d889.pdf (accessed 12 September 2024).

Telenko, C., Wood, K., Otto, K. et al. (2016). Designettes: an approach to multidisciplinary engineering design education. *ASME Journal of Mechanical Design* 138: 022001-1–022001-11.

Unido (2020). Industry 4.0 opportunities behind the challenges background paper. https://www.unido.org/sites/default/files/files/2020-06/UNIDO%20Background%20Paper%20on%20Industry%204.0_FINAL_TII.pdf (accessed 12 September 2024).

Venneslan, C. (2009). Electrification and industrialization: an assessment of the industrial breakthrough in Norway. *Scandinavian Economic History Review* 57 (2): 124–155.

Vrabič, R. and Butala, P. (2012). Assessing operational complexity of manufacturing systems based on statistical complexity. *International Journal of Production Research* 50 (14): 3673–3685.

Wiboqo, E.B., Legionosuko, T., Mahroza, J., and Jaya, Y.C. (2020). Industry 4.0 and opportunities in competency development for defense apparatus' human resources. *International Journal of Advanced Science and Technology* 29 (7): 45–60.

Wikipedia (2024). Mechatronics. https://en.wikipedia.org/wiki/Mechatronics (accessed 12 September 2024).

Yan, X.-T., Bradley, D., Russel, D., and Moore, P. (2020). *Reinventing Mechatronics – Developing Future Direction for Mechatronics*. Switzerland AG: Springer Nature.