Hindawi Publishing Corporation
Advances in Mechanical Engineering
Volume 2013, Article ID 702590, 10 pages
http://dx.doi.org/10.1155/2013/702590

Research Article

Integrated Knowledge-Based System for Machine Design

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Received 22 April 2013; Revised 6 August 2013; Accepted 16 August 2013

Academic Editor: Dongxing Cao

An integrated design system (IDS) approach has been developed to integrate various stages of the mechanical design process, including rapid prototyping. The system consist, of design, analysis, calculation, rapid prototyping, and library modules, and it blends artificial intelligence methods, CAD-CAM, and technical computing packages into a single environment. The system has been applied for the design of one-stage gearbox with helical gear. In this case study, all stages of the design process are carried out by using IDS.

1. Introduction

The design process of the mechanical products is tedious and time consuming because of the various stages and complex activities involved. On the other hand, there are strong pressures to reduce overall costs in a competitive market environment [1]. But, the traditional design approach is inadequate in meeting these needs. Today a lot of CAD/CAM/CAE application software, different databases, and web-based services are used for the mechanical design studies, but these technologies are distributed and there is no coordination between them. Therefore, a number of researchers have focused their studies on establishing a cooperative and integrated environment. Su and Wakelam studied an intelligent hybrid system for integration in design and manufacturing. Their approach blends a rule-based system, artificial neural networks, genetic algorithm, hypermedia, and CAD/CAE/CAM packages into a single environment [2]. Zhao et al. described an agent-based approach to systems interoperability in cooperative design systems [3]. Hao et al. developed an agent-based collaborative e-engineering environment for product design engineering. They studied a prototype software system based on the web and a software agent and demonstrated its viability through an industrial case study [4]. Myung and Han introduced the feature representation, a concept of design unit, parametric modeling, and configuration design methods, and they proposed a framework of a design expert system, which describes parametric modeling with design knowledge-based [5]. Ramamurti et al. put forward an integrated system that could be used by the user for the complete design and analysis of a mechanical system. The system consists of two parts, such as initial design and detailed analysis [6]. Zha and Du presented an integrated method and assembly planning. They applied the system as an integration model, and so, CAD/CAM applications in assembly were supported [7]. Chiang et al. proposed a general integrated framework of design knowledge representation and developed a knowledge-based intelligent system to facilitate dynamic design reasoning. Also, they presented a case study of designing a mechanical system to demonstrate the features of the developed system [8]. Chung et al. studied a framework for integrated mechanical design automation, and they developed extended variational design technology using graph theory and numerical solution techniques [9]. Liang and O'Grady studied the object-oriented approach. Their study contained both of the fundamentals of object-oriented design in the development of design process models [10]. Zha et al. proposed a knowledge-based approach and developed an expert design system to support top-down design for assembled products. The proposed approach focused on the integration of product design, assemblability analysis and evaluation, and design for assembly with economical analysis [11]. Chen et al. developed an intelligent approach for generating assembly drawings automatically from three-dimensional computer assembly models of mechanical products by simulating the experienced human designer's thinking mode with the aid of computer graphics and a knowledge-based expert system [12]. Daabub and Abdallah presented a computer based intelligent system so that the design for assembly can be realized within a concurrent engineering environment. They developed an expert system that supports new techniques for design and for assembly, and the developed system gave users the possibility to assess and reduce the total production cost at an early stage during the design process [13]. Wang et al. described a new framework for collaborative design. This framework adopts an agent-based approach and relocates designers, managers, systems, and the supporting agents in a unified knowledge representation scheme for product design [14]. Wang and Zhang aimed to develop a distributed and interactive system, on which designers and experts can work together to create, integrate, and run simulations for engineering design. Karayel et al. purposed an internet-based intelligent agent system for mechanical design [15]. The reference model and the architecture of the system were developed [16]. The current study can be accepted as a detailed part of this general research. Karayel et al. studied to determine factors affecting safety stress in the machine design by using artificial intelligence technologies [17]. Cao and Fu proposed and employed a design synthetic approach to guide the design process via behavioral reasoning and to obtain an iterative transforming process. They presented the functional representations and design parameters according to the design requirements of a product and established a behavioral matrix model by using the bond graph fundamental elements and then presented a knowledge modeling language for behavioral reasoning. They developed a prototype system for a computer-aided conceptual design and presented an application from the industry consequently [18]. Cao et al. presented an agent-based approach for guiding the mechanical product conceptual design. Firstly, they analyzed the mechanical product design requirements and then gave functional parameters and design variables and proposed a behavioral matrix model using bond graph fundamental elements. After, they established an agent-based framework and so aimed at solving the behavioral matrix model, producing functional means tree and multisolutions with the aid of agent technologies. An application for the special jig design in the machine center was presented as an example of the design synthesis [19]. Goel et al. analyzed CAD dimensions, such as cognitive design, collaborative design, conceptual design, and creative design. Then, they developed a knowledge-based CAD system illustrating CAD characteristics, and this system was called Design by Analogy to Nature Engine (DANE). They proposed that DANE is an important assistant to assess the practical use of CAD dimensions. One of the major contributions of DANE is to provide human interaction with knowledge-based CAD systems [20]. Chen et al. presented a multilevel model for an entirely assembly design. Their model captured abstract information, skeleton information, and detailed information, so that it can effectively support assembly design. This assembly design process contained design steps with an assembly tree structure. They discussed the use of assembly design model for extending the scope and deepness of its application [21]. Jia et al. proposed a novel multilevel system representation modeling framework for supporting design methods. Their framework had the capability to integrate the product design CAD models. Also, the data exchange and transfer in multidomain analyses were made possible by using the framework. The authors illustrated the framework with a case study. So, the applicability of the modeling framework was highlighted for multibody mechanical systems [22]. Li et al. discussed an integrated design method, which thoroughly considers related parameters of the various subsystems in order to optimize the overall system that mainly consists of optomechanical structure CAD, CAE, and the integrated information platform PDM. Their method was based on the model transformation and data share among different design and analysis steps, and so they carried out concurrent simulation and design optimization. Also, they presented an example of application of a mechanical structure [23]. Zheng et al. developed a novel collaborative design approach to improving efficiency. They designed and implemented a prototype system CoAutoCAD to test the approach and to demonstrate a variety of collaborative design activities [24]. Zhongtu et al. described a declarative modeling approach for task implementation and a methodology for problem-solving of knowledge primitives in design task. In the study, task analysis, knowledge management, and design object management module were developed and integrated with a mechanical computer-aided design (MCAD) system. The two-stage gearbox design was given as an example for this approach [25]. Al-Ashaab et al. developed a knowledge-based environment (KBE) to support product design validation of refresh projects, and they implemented KBE on the product lifecycle management platform. This implementation prevented repeating unnecessary and costly physical product tests, and so it also reduced time and costs for these refresh projects [26]. Chandrasegaran et al. aimed to review the product design process. They focused on a time frame of the last 20 years in general and the last decade more specifically, in order to balance the breadth and depth of the review, relaxing the time frame where it was necessary to look further in the past to establish relevance [27]. Rocca presented a broad technological review of knowledge-based engineering (KBE) in the attempt to fill the current information gap. In this study, the artificial intelligence roots of KBE are briefly discussed, and the main differences and similarities with respect to classical knowledge-based systems and modern general purpose CAD systems are highlighted. Finally he investigated evolution and trends of KBE systems and provided a list of recommendations and expectations for the KBE systems of the future [28]. Chen et al. aimed to develop a knowledge-based framework for the creative conceptual design of multidisciplinary systems through reusing and synthesizing known principle solutions in various disciplines together. The framework contained a formal constraints-based approach for representing the desired functions, a domain-independent approach for modeling functional knowledge of known principle solutions. The success of the system was explained with a design case study [29]. Lee et al. prepared a new and efficient collaborative intelligent computer aided design (CAD) framework in a theoretical study. Their study made an effort for minimizing redundant design stages and design bottlenecks using the design history, while a lot of collaborative CAD frameworks aimed at decreasing the waiting time for updating design among collaborative designers. Also, it generated an efficient reverse-engineered process, while resolving other existing collaborative design issues [30]. Wang et al. presented a new approach of parametric collaborative design based on the analysis of the many disadvantages in serial design for concurrent engineering and developed an overhead travelling crane's parametric collaborative design system for concurrent engineering. The feasibility, availability, and effectiveness of the system were validated by the results obtained from the case study [31]. Wang et al. presented the solution of collaborative simulation environment (CSE) and analyzed its function framework and system architecture. They researched multihierarchy engineering data management (EDM) and simulation flow control. Then, the flow model platform and web portal of some suspension systems CSE were developed in the paper. Finally, they proposed that the product simulation period was shortened and the design efficiency was increased [32]. Zhang et al. proposed an intelligent design system for complex mechanical product. The intelligent design system adopted product family case tree to construct the model of complex mechanical product and case-based reasoning technology to reuse successful product design knowledge. Product design system was constructed by using the engineering database technology. After that, they realized the intelligent crane design platform by Visual Basic.NET programming, and so, saw that the application example demonstrated the feasibility of the approach [33].

This study is part of a comprehensive project which has many subsystems. Here, the general framework of the project is described, and the integration of the subsystems is focused on. When all the processes about the project are completed, it can operate as an intelligent interactive system. In this study, the subsystems such as design, analysis, computation, and rapid prototyping are prepared, and each of them can fulfill its function now. It is an important prerogative of the study that the user can realize all the processes on a single platform. The users can utilize both subsystems individually and can utilize the whole system with little user intervention for now. On the other hand, the system has a suitable structure for users of all levels because all design and prototyping tools used in the system are chosen from practical applications. This case is a difference of the system too. At the same time, the system uses the current training materials; therefore, this study can be used for the training of machine design with small adaptations. This also is another distinctive feature of this study. This study provides an intermediary to integrated different engineering tools such as CAD/CAM packages, technical computing and analysis packages, and databases and knowledge bases. This study is organized as follows: at first, an introduction and literature review are presented. Section two gives a background about the engineering design process. Section three illustrates integrated design system (IDS). Section four presents an implementation of IDS, and section five describes the conclusions of the study and future works.

2. Background of the Engineering Design Process

Engineering design can be defined as the realization of a product which satisfies a certain need [17]. In other words, the first objective of any engineering design project is the fulfillment of some human need or desire. Engineering may be described as a judicious blend of science and art, in which natural resources, including energy sources, are transformed into useful products, structures, or machines that benefit humankind [34]. It is a good design if its product works efficiently and economically within the imposed constraints. The major constraints are cost, reliability, safety, level of performance, legal requirements, sociological considerations, pollution, and energy consumption. Also, engineering design is not a process consisting of only one phase. On the contrary, it is an iterative process involving a series of decision-making steps where each decision establishes the framework for the next one. It is a continuum effort which embodies stages such as preliminary design, intermediate design, detail design, and development. The engineering design process starts with product specification and goes through an interactive process of requirements analysis, conceptual design, detailed design, and design analysis, and it ends with a functional product that fulfills the product specification [9]. Each stage has submodules that are different from each other, and therefore a designer is not expected to be an expert on all stages. However, a successful designer either should be able to communicate effectively with various specialists in the different stages or should utilize an integrated system consisting of expert systems corresponding to design stages. The present study considers detail design and purposes to develop an integrated design system.

3. Integrated Design System (IDS)

The IDS is the detail design module of the model of integrated design system for mechanical design. The flow chart of the IDS is in Figure 1 and its input screen is in Figure 2. The IDS involves submodules such as calculation, analysis, modeling and drawing, rapid prototyping, and library as seen in Figure 3.

All modules are interactive with each other. The calculation module of the IDS is used for engineering calculation, such as dimensions of machine elements and the calculating of the design safety stress. The 3D modeling and 2D drawing of the products can be prepared by using the design module of the IDS. This module uses CAD/CAM software packages such as SolidWorks and Catia. The analysis module of the IDS can perform the numerical analysis of the mechanical system using finite element methods such as Abaqus and Ansys. The library module of the IDS consists of material database, standard tables and diagrams, systematic technical knowledge and firm catalogues and supports the other modules. The final product of the design process can be transformed into a real physical model by using rapid prototype module of the IDS.

Knowledge Representation and Data Transfer of Integrated Design System (IDS). Automatic data transfer between

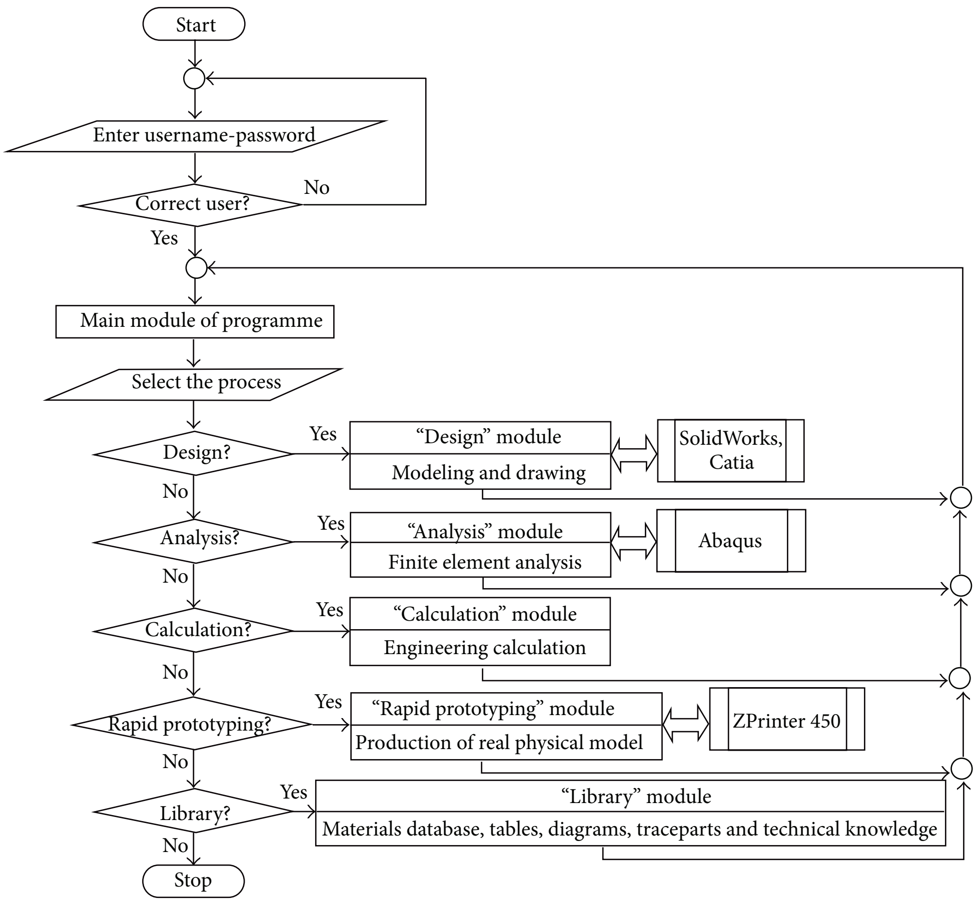


Figure 1: The flow chart of the IDS.

Figure 2: The input screen of the IDS.

Figure 3: The user interface of the IDS.

the units has been carried out using the software agents. In the study, software agents are programs that can perform specific design tasks for a user and possesses a degree of intelligence that permits it to perform parts of its task autonomously and to interact with its environment in a useful manner. There are software agents for each task, and so it can be possible to transfer the knowledge and to use it collectively. The communication and coordination between agents requires a standard knowledge protocol. For this reason, the knowledge exchange schemes and the knowledge forms have been prepared. The design knowledge is determined into specific codes. This knowledge is categorized into main articles and subarticles according to their themes. Also, the activities of knowledge exchange between agents have been categorized and have been prepared into certain formats, such as from who to whom, what is the purpose, and what is the answer. The knowledge protocol layers, which are used by agents of mechanical design, consist of definition, query, and result layers. This knowledge protocol is presented in Figure 14. It is very important that the design knowledge must be prepared into suitable documents so that they can be converted to

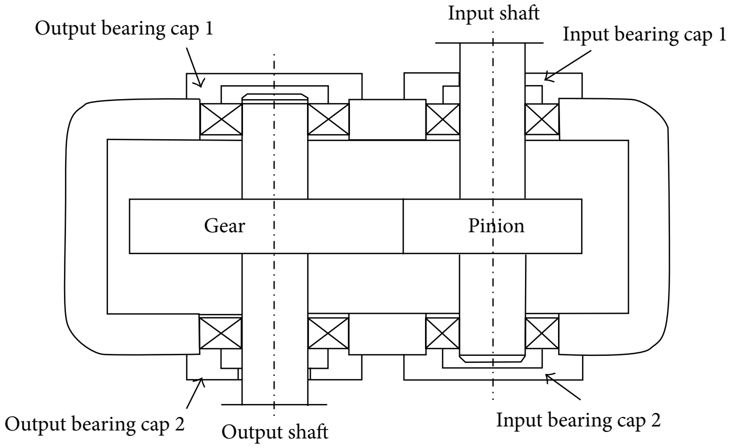


Figure 4: Layout of one-stage gearbox.

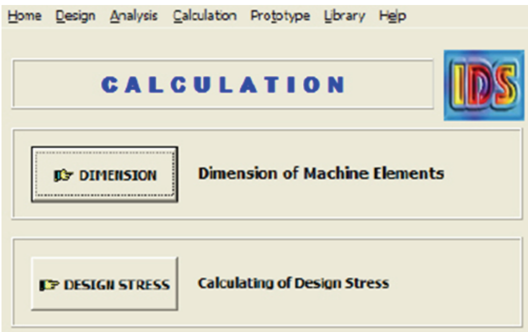


Figure 5: The calculation module of the IDS.

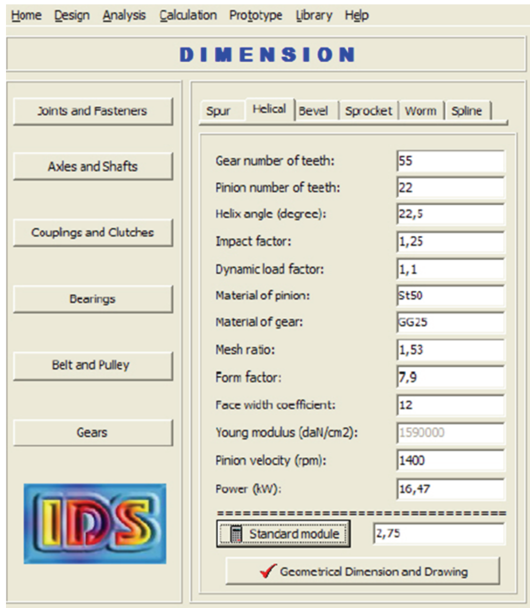


Figure 6: The screen of the gear pair.

digital signals easily because the knowledge stream is in digital form. Therefore, the documents which are the defining address of the knowledge and its position number have been prepared.

4. Implementation of the Integrated Design System

In this study, the design of one-stage gearbox with helical gear has been chosen as a design case study to illustrate and test the developed system. The aim of this section is to use the developed system for the complete design and analysis of the gearbox. The gearboxes are used to transmit power and to change speed, and these have an extensive application area such as materials handling, transportation, metallurgical, and chemical engineering. Also, the gearboxes contain the principal machine elements such as gears, shafts, bearings, bearing caps, bolts, and keys and represent a comprehensive mechanical system. Therefore, the gearbox has been selected for this case as an example. Figure 4 shows the layout of the gearbox.

The graphic user interface (GUI) has been prepared to allow the user to select the design stages (Figure 3). First, the dimensions of each element of the gearbox are calculated. Then, these are drawn according to the calculated dimensions. After, these elements are analyzed and the part dimensions are considered again in case of need. The assembly of the gearbox is realized finally. The last stage of the design process is prototyping the whole gearbox together with all the elements. The use of the IDS has been described in accordance with the elements of the gearbox, which is shown in Figure 4.

4.1. Gear Design. The design of the gear pair begins with the calculation of the gear dimensions, and so the calculation module has been selected from GUI, and then a new window is opened as seen in Figure 5.

The calculation module consists of the dimension and the design stress submodules. When the dimension module is selected from here, second new window containing the machine elements is open, as shown in Figure 6. Again,

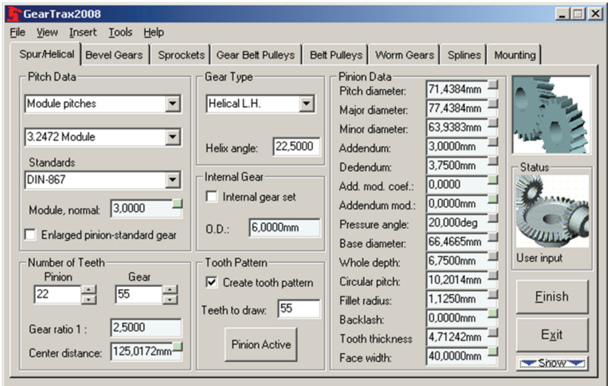


Figure 7: The screen for the geometrical dimension and drawing of the gears.

the gears are selected from this window and the input data of the gear pair are entered.

In the calculation of the gear mechanism, the pinion has been considered because it is forced more than the other gear. The corresponding gear can be selected accordingly [6]. The module of the gears (m) is calculated using the equations according to bending stress and contact stress as shown in the following.

The module according to bending stress:

$$m_{n1} = 6 \cdot \sqrt[3]{\frac{k \cdot \zeta \cdot M_b \cdot \gamma_n \cdot \cos \beta_0}{Z_1 \cdot \sigma_{em} \cdot \psi \cdot \varepsilon_p}}, \quad (1)$$

and the module according to contact stress:

$$m_{n2} = 9 \cdot \sqrt[3]{\frac{k \cdot \zeta \cdot M_b \cdot E\,(i+1) \cdot \cos^4 \beta_0}{Z_1 \cdot P_{em} \cdot i \cdot \psi \cdot \varepsilon_p}}. \quad (2)$$

The design of the gears is done in two steps: step 1 is to determine the module and step 2 is to calculate the geometrical dimensions and drawing. The module of the gears can be easily determined when the input data of the gear pair are entered and the standard module icon is clicked, as shown in Figure 5. The IDS calculates the module (m) by means of (1) and (2). The system accepts the maximum of two values obtained from equations as the module (m) and selects standard module. When the geometrical dimension and drawing icon is clicked, the new window is opened for entering geometrical data, as seen Figure 7.

GearTrax is a submodule of the SolidWorks software package and is used for the geometrical dimension and drawing of the gears. The designed gears are presented in Figure 8. The design of shafts, the bearings, and the keys is achieved in two stages, as the dimensional calculating and geometrical forming. The geometrical forming of these elements depends on each other, and so this process is postponed until the second stage.

4.2. Shaft Design. There are two shafts belonging to the pinion and the gear in the assembly of the gearbox. The design methods of these shafts are the same as each other. Therefore, one of these is described more in detail than the other. The diameter of the shaft can be automatically calculated using the dimension module of IDS. When the axles and shafts icon of this module is clicked, a new window is opened, as shown in Figure 9. In this window, if the input parameters of the shaft are written, the diameter of the shaft can be obtained. The shafts are forced by the combined torsion and bending load because these are required to transmit the torque, as well as withstanding the bending stresses due to the gear teeth loads and bearing reactions. The shafts are modeled as beam elements, and so their diameters are calculated. The diameter of the shaft (d) is given by

$$d = \sqrt[3]{\frac{32 \cdot M_B}{\pi \cdot \sigma_{em}}}, \quad (3)$$

where M_B is combined moment and σ_{em} is safety stress. The combined moment consists of the bending moment M_e and the twisting moment M_b and it is given by

$$M_B = \sqrt{M_e^2 + \frac{1}{2} M_b^2}. \quad (4)$$

4.3. Bearing Design. The use of the radial ball bearing is suitable. The gearbox has two shafts as the input shaft and the output shaft, and four bearings are required for these shafts. Because the load is applied from the middle of the shaft, the bearings belonging to the same shaft are forced with the same loading value. Therefore, the bearings to be selected are two types for the input shaft and the output shaft. The bearings can be selected by using the axles and shaft icon of the dimension module of IDS, as seen in Figure 10.

When the bearing parameters are entered and the select icon is clicked, the calculation of the bearing is realized and the suitable bearing can be selected. For this process, the principal bearing equations used by the software of the IDS are as follows. For the deep grove ball bearing the equivalent dynamic load, F_{es} is given by

$$F_{es} = X \cdot F_r + Y \cdot F_a, \quad (5)$$

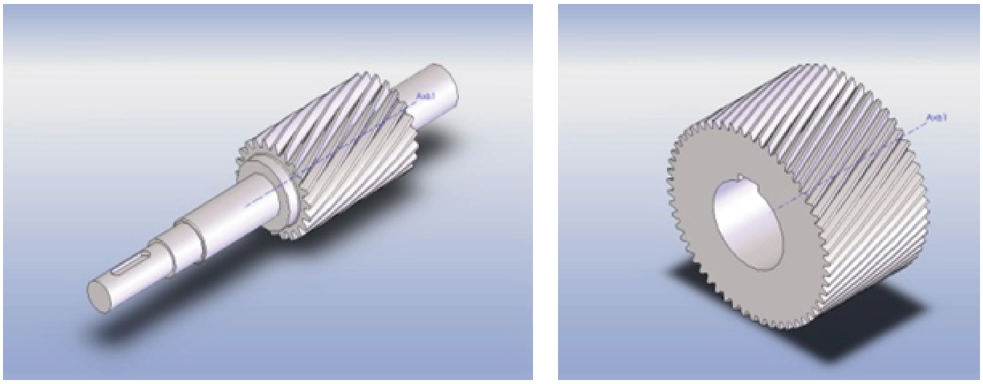
where X, Y, F_r, and F_a are radial factor, thrust factor, radial force, and axial force, respectively.

The basic dynamic load rating is

$$C = F_{es} \sqrt[3]{L}, \quad (6)$$

where L is life of bearing. Finally, IDS selects the suitable bearing according to the diameter of the shaft and the dynamic load rating from the catalogue in the library module of the IDS.

4.4. Key Design. When power is supplied from the rotating shaft, it is necessary to attach gears to the shaft. To prevent relative rotation between the shaft and the gear, the connection between the gears' hub and the shaft must be secured [35]. Here, the parallel key is used to prevent relative rotation. Recommendations for key width and height, as a function



(a) (b)

Figure 8: The designed gears: (a) the pinion and (b) the gear.

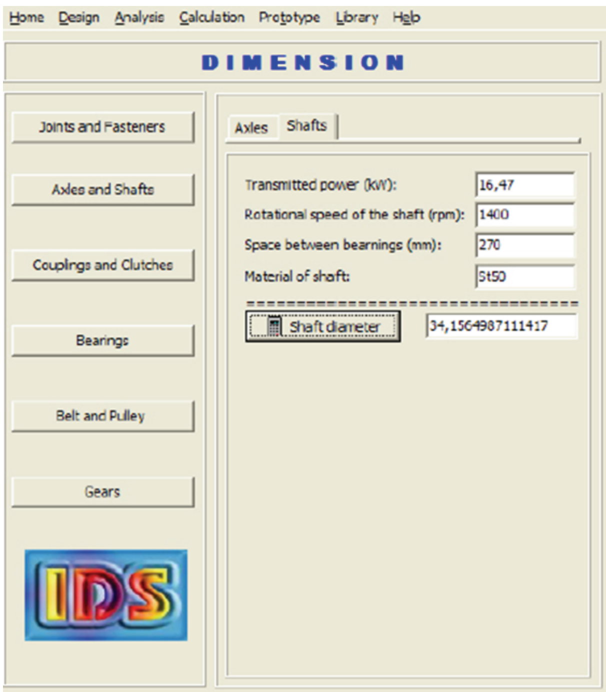


Figure 9: The calculation screen of the shaft diameter.

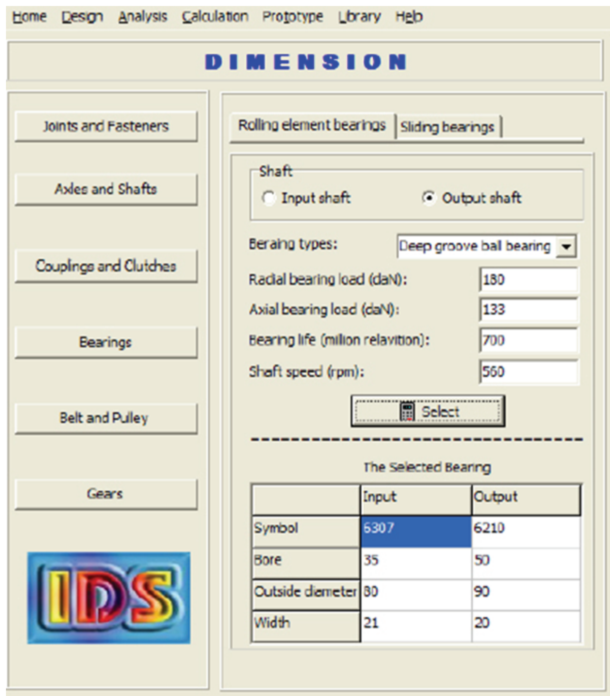


Figure 10: The screen for the selection and the design of the bearings.

of shaft diameter, are provided by standards, as shown in Figure 11. The key length (l) is obtained as a function of the transmitted torque. The key is forced by the shearing stress and the comprehensive bearing stress. Therefore, the calculation of the key length is based on these stresses. These processes about the key are realized by the dimension module of the IDS, as shown Figure 11.

4.5. Geometrical Forming and Assembly. The geometrical forming of the parts of the gearbox and their assembly are achieved by the design module of the IDS. This consists of two submodules such as SolidWorks and Catia for present, as seen in Figure 12.

SolidWorks is used for the current study, and the assembly of the gearbox into 3D is presented, as seen in Figure 13. Due to pages limitation of the paper, the analysis and rapid prototyping module of the IDS could not be discussed. However, the numerical analysis of the designed products can be carried out, and both the elements and the assembly of the gearbox can be produced as a prototyping by using ZPrinter 450 machine connected to the IDS.

5. Conclusion

This study is the first part of a comprehensive project which has many subsystems. Here, the general framework of

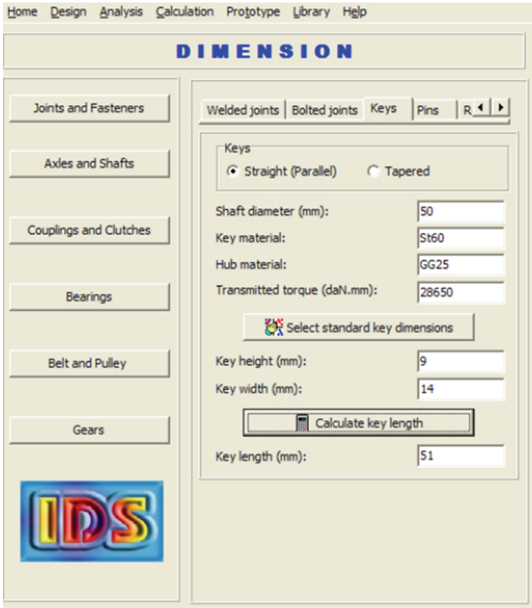


FIGURE 11: The screen for the key design.

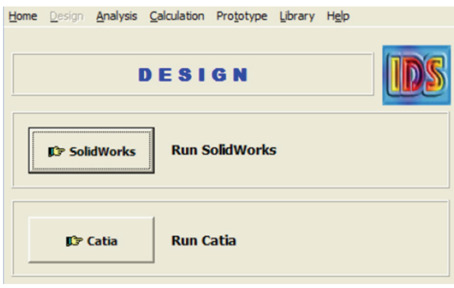


FIGURE 12: The design module of IDS.

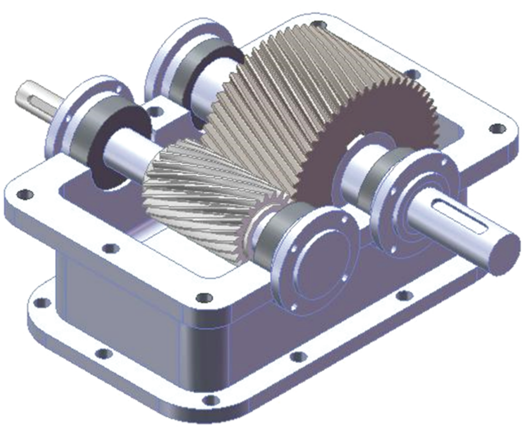


FIGURE 13: The assembly of the gearbox.

the project is described and the integration of the subsystems is prepared. When all processes related to the project are completed, it can operate as an intelligent interactive system. In this study, the subsystems such as design, analysis, computation, and rapid prototyping are prepared, and each of them

From		To		Definition
0101		0104		
Aim	Question		Task	Query layer
0 (question)	001		001	
	002		002	
	003		003	
1 (answer)				
2 (knowledge)				
Knowledge source	Response status		Response signal	Response layer
D0104020803	01		01 (done)	
D0104020301				
. . .				
. . .	02		02	
. . .				
	00		00 (wait)	

FIGURE 14: The knowledge protocol.

can fulfill its function now. It is an important prerogative of the study that the user can realize all the processes on a single platform. The users can utilize both subsystems individually and can utilize the whole system with little user intervention for now. On the other hand, the system has a suitable structure for users of all levels because all design and prototyping tools used in the system are chosen from practical applications. This case is a difference of the system too. At the same time, the system uses the current training materials; therefore, this study can used as a course tool for the training of machine design if the small adaptations are realized on the system. This also is another distinctive feature of this study. Also, all stages of the design of the gearbox have been achieved by using the IDS only, and so the IDS has been tested. It is expected that the IDS will be a favorable computer aided tool for industrial users because it reduces the design cost, design errors, and time to market. The next works about this subject will be focused on the intelligent features of the system.

Nomenclature

M_b: Torsional moment, N·m
E: Elasticity module, Pa
β_0: Helix angle, radians.

Subscripts

k: Impact factor
ζ: Dynamic load factor
Z_1: Number of teeth of gear
ψ: Dimension factor
ε_p: Engage ratio
γ_n: Form factor
i: Gear ratio.

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