# 计算机数字控制技术

# Computer Numerical Control Technology

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## 内 容 简 介

本教材按照数控机床的主要工作流程编写，详略得当；重运用、强实践，将抽象的原理与实际应用有机结合；追踪先进技术的发展，涵盖智能制造技术最新成果。关键词语采用双语说明方式。

本教材共有5章，包括数控机床发展史、数控系统工作原理、伺服系统结构及工作原理、机械结构、智能制造等内容。教材还包含实验指导书，强化对学生实践创新能力的培养。



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# 前 言

中巴、中非友谊源远流长，加大教育国际援助力度，具有针对性地开展紧缺教学资源建设，不仅可以提高多层次、宽领域的国际教育水平，而且有助于增进国际友谊，为“一带一路”合作绘制“工笔画”。

数控技术作为先进制造领域的核心技术，是教育援外机械专业本科生和研究生的必修知识。然而，现有数控技术课程双语教学资源不足，现有教材出版日期较早，缺乏先进数控技术及应用等方面的知识。为填补本领域空白，有针对性地为发展中国家培养数控技术人才，特编写本教材。

本教材分为5章，主要涵盖数控机床发展史、数控系统工作原理、伺服系统结构及工作原理、机械结构、智能制造等内容。本教材按照数控机床的主要工作流程编写，详略得当；重运用、强实践，将抽象的原理与实际应用有机结合；追踪先进技术的发展，涵盖智能制造技术最新成果。关键词语采用双语说明方式。可以作为中巴、中非合作办学的机械工程专业留学生专业教材、高年级本科生双语教材，也可以供数控技术人员自学参考。教材包含实验指导书，强化学生实践创新能力的拓展。

本教材第1章由天津职业技术师范大学赵巍、旁遮普天津技术大学 MUHAMMAD ALI MANSOOR 编写；第2章由天津职业技术师范大学赵楠、旁遮普天津技术大学 MUHAMMAD KASHIF IJAZ 编写；第3章由天津大学董靖川编写；第4章由天津职业技术师范大学赵巍、张翔宇，旁遮普天津技术大学 RAMEEZ UL HASSAN 编写；第5章由天津职业技术师范大学刘鹏鑫、赵楠，湖州职业技术学院王英杰编写。全书由付晓燕校稿，旁遮普天津技术大学 Dr. Syed Asim Ali Shah、天津职业技术师范大学满佳老师、北京格瑞纳电子产品有限公司赵伟工程师以及研究生刘梦莹、王丽娜、何苗等也参与了本教材的审核、编辑等工作。

在教材的编写过程中参考了一些数控技术相关的教材和资料，特向其作者表示真诚的感谢。鉴于作者水平有限，书中不可避免地存在缺点、不足，敬请各位读者批评指正。

编 者

2019年1月

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# Chapter 1　Introduction

## 1.1　The history of numerical control machine tools

shù kòng jī chuáng shǐ

（数控机床史）

To assist in engineering calculating, a computer was developed at the University of Pennsylvania in 1946. It was called Electrical Numerical Integrator and Calculator which consisted of huge mass of tubes and wires. Although it was slow and stood no comparison with modern computers, it was the best at that time.

The birth of Numerical Control (NC，数控) is generally credited to John T. Parsons, a machinist and salesman at his father's machining company, Parsons Corp. In 1942, *The United States Air Force* signed a contract with Parsons Corporation to build the wooden stringers (or ribs, see Figure 1-1) in the rotor blades（转子叶片）(only 17 points were given to define the outline of stringers), but one of the blades failed. Parsons suggested a new method, which led him to consider the possibility of using stamped metal stringers instead of wood. A device would not be easy to produce given the complex outline. Looking for ideas, Parsons visited Wright Field to see Frank Stulen, the head of the Propeller Lab Rotary Wing Branch. Stulen's brother worked at Curtis Wright Propeller, and mentioned that they were using punched card calculators for engineering calculations. When Parsons saw what Stulen was doing with the punched card machines, he asked Stulen if they could be used to generate an outline with 200 points instead of the 17 they were given, and offset each point by the radius of a mill cutting tool. If you cut at each of those points, it would produce a relatively accurate cutout of the stringer（横梁）. This could cut the tool steel and then easily be filed down to a smooth template for stamping（冲压）metal stringers.

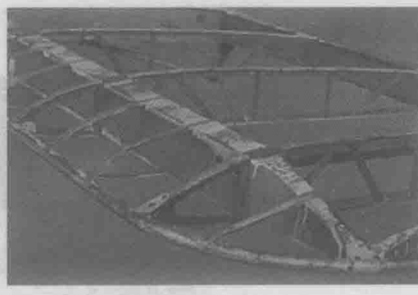


**Figure 1-1　One kind of ribs**

Stulen made the program for the stringer which is comprised of large table consisting of numbers, without any problem. Later the program was communicated to machine. There are three operators: one reads the card while other two move the tool in

X-axis and Y-axis to follow the cutting profile. For each pair of numbers, the operators had to move the cutting head to the indicated spot and then lower the tool to make the cut. This was called the "by-the-numbers method"(数字控制技术), or more technically, "plunge-cutting positioning"(切入式定位). It was a labor-intensive prototype of today's 2.5-axis machining.

At that point, Parsons conceived of a fully automated machine tool. With enough points on the outline, no manual working would be needed to make it.

In 1949, the Air Force arranged funding for Parsons to build his machines, but he was confronted by the problem that had prevented convergence of Jacquard-type controls with machining.

In the spring of 1949, Parsons turned to Gordon S. Brown's Servomechanisms Laboratory at MIT, which was a world leader in mechanical computing and feedback systems(反馈系统).

A tripartite agreement was arranged between Parsons, MIT, and the Air Force. In March 1952, the MIT Labs held the first demonstration of the NC machine using a punched tape(穿孔带) to generate the movement of three axes. See Figure 1-2.

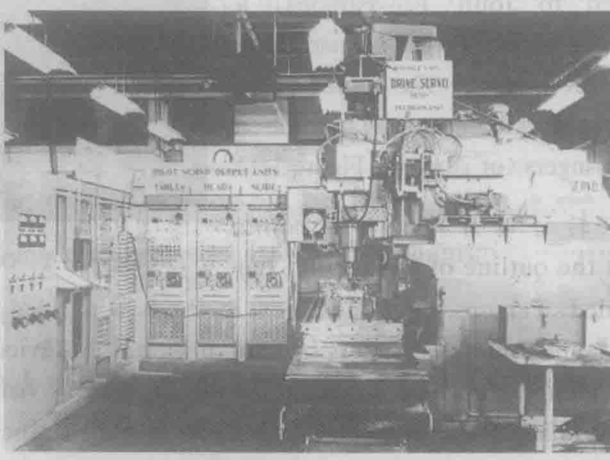



**Figure 1-2 The first successful NC machine, developed by MIT**

## 1.2 Basic principles

### 1.2.1 The principle of computer numerical control(CNC) machine tools

1. Preparing stage

Manufacturing data is determined by the parts drawing and technical requirements, including tool trace coordinates, spindle, feed, cutting depth, tool and so on. Other auxiliary data, for example, tool changing, workpiece clamping(夹紧) and release(松开), cooling, lubrication, is defined, too.

2. Programming stage

For computer numerical control(CNC,计算机数控) machining, programs are written in forms of G-code and M-code, which are the understandable languages of CNC system. For instance, G00, G02, M03, M30 and so on.

3. Transmitting stage

The programs are transmitted into CNC system through the tape (outdated), disk, Internet and so on.

4. Machining stage

When the program runs, it translates codes into signals which drive the motors accordingly. The motors then move the workpiece and cutting tool to get desired dimensions required.

### 1.2.2 The definition of numerical control

Numerical control(NC,数值控制,简称"数控") is also called digital control (数字控制). NC technology is to use digital information to realize controlling automation. NC has been widely used in trajectory control of the mechanical movement and switching control of the mechanical system, such as robots, machine tools, production lines and so on. The objects controlled by digital information are varied, but the NC machine tools are the most typical NC equipment.

What are NC machine tools? They mean the use of digital signals to control the machine movement and process.

What are CNC machine tools? They are developed with microprocessors or special computers as NC systems. The control system carries out automatic machining of the workpiece. Today, all the machine control units are based on the computer technology.

In CNC machine tools, digital codes, including numbers, letters and symbols, are taken to express the workpiece dimensions and a variety of operations, such as setting spindle speed, loosening or fastening the cutter, setting feed rate, shutting on or off the coolant automatically, running or stopping the program, etc. And then digital codes are transmitted into the NC device through the control medium (disks, serial ports, network). The NC device deals with the input information and performs calculation, then sends a corresponding control signal to the servo system or other driving components for automatic machining the workpieces. The CNC structure is shown as Figure 1-3.

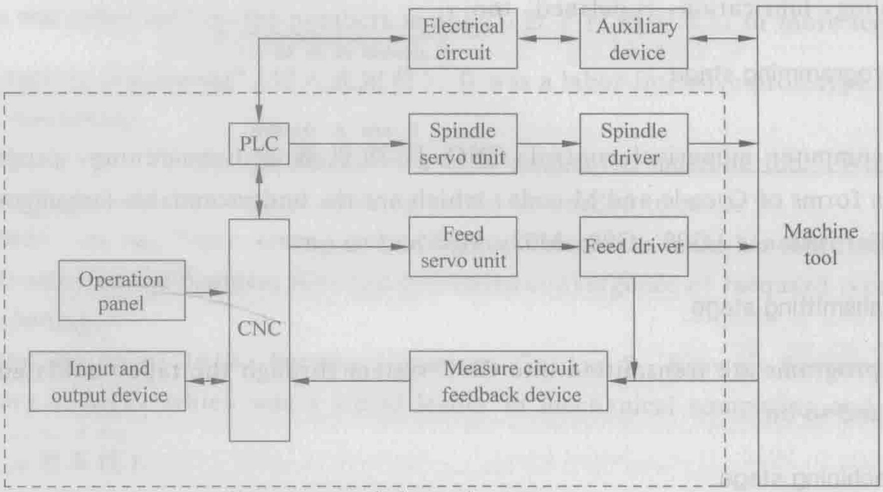



**Figure 1-3 CNC system structure**

## 1.3 The characteristics of CNC machine tools

1. Adaptability

Adaptability also means flexibility, which refers to that the CNC machine can adapt to different jobs very well. For every new part, we only need to rewrite the program and enter the new one to complete the machining of the new part without changing the mechanical part and the control part. The production process is done automatically. This provides a great deal of convenience for single part, small batch production and trial production of complex structural parts. Strong adaptability is the most prominent advantage of CNC machine tools, which resulted in its rapid development.

2. High precision and stability

Firstly, compared with manual machining method, CNC reduces or eliminates operator's influences. Secondly, during the design and manufacture of CNC machine tools, a number of measures are taken to achieve high accuracy and stiffness for the mechanical parts and structure. The pulse equivalency normally reaches 0.0001—0.01 mm, and CNC machining accuracy has varied from the past ± 0.01 mm to ± 0.001 mm or even higher due to the compensation of the chain reverse gap and screw pitch error realized by the NC device. In addition, the stiffness and thermal stability of transmission system and the machine structure are higher for the CNC machine tool. In particular, the batch production consistency is improved remarkably, so high product qualification and stability is achieved.

3. Higher automation, lower labor intensity

CNC machine tool operations can be carried out automatically by the control program. The operator only needs to set the job and tool and the rest is done by the program. The operator just observes the process and performs inspection, which has greatly reduced the labor. In addition, instead of being open for the conventional machine, CNC machine tool is generally closed during processing, which are both clean and safe. Today CNC machines are available in esthetic colors ranging from green to gray or white.

4. Higher efficiency, shorter machining and auxiliary time

Parts processing time mainly consists of machining time and auxiliary time. CNC machine tools are equipped with wide range of spindle speeds and feeds, so for each process we can choose the most appropriate setting. Due to the rigidity of the CNC machine tool structure, it is allowed to carry out the strong cutting, which improves the cutting efficiency and saves the machining time. Auxiliary time is also reduced as compared with the conventional machine, for example, fast movements and shorter workpiece clamping time result in much shorter automatic tool change time.

In addition, an automatic tool changer made it possible to carryout multi-order continuous processing without any delay.

5. Being conducive to the modernization of management

In the CNC machine tools, digital information and standard codes are used and transmitted, which lays the foundation for computer-aided design/manufacturing and management integration.

## 1.4 Introduction to main CNC machine tools

With regard to the manufacturing process, CNC machine tools include CNC lathes, CNC milling machines, machine enters, CNC drilling machines, CNC boring machines, CNC grinding machines, CNC electric discharge machines, CNC wire-cut electric discharge machines, CNC laser beam machines, CNC punching machines or punching presses, CNC ultrasonic machines, CNC gear holling machines, CNC plasma cutting machines, CNC bending machines, CNC water cutting machines, parallel machine tools, coordinate measuring machines and so on.

The most common CNC machine tools are introduced as follows.

1. CNC lathes（数控车床 shù kòng chē chuáng）

A CNC lathe（see Figure 1-4）includes spindle（主轴 zhǔ zhóu），slide plate（溜板 liū bǎn），tool-holder（刀架 dāo jià）and so on. CNC system，including LCD panel（液晶显示屏 yè jīng xiǎn shì píng），control panel（控制面板 kòng zhì miàn bǎn），electrical control system（电气控制系统 diàn qì kòng zhì xì tǒng）.

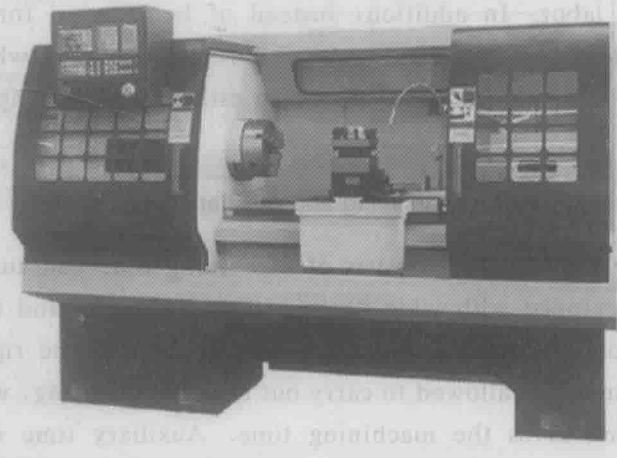


**Figure 1-4 CNC lathe**

CNC lathe generally has two-axis interpolation function. Z-axis is parallel to the direction of the spindle axis while X-axis can move vertically to the spindle. The latest turning and milling center with a C-axis can turn and mill the workpiece automatically with the milling cutter placed in the tool turret.

The CNC lathe is mainly used to process shaft or disc parts，such as cutting the inner and outer cylindrical surface，cone surface，thread surface，end surface，groove，chamfering，etc. For the rotary bodies，drilling，reaming and boring can also be done.

2. CNC milling machines（数控铣床 shù kòng xǐ chuáng）

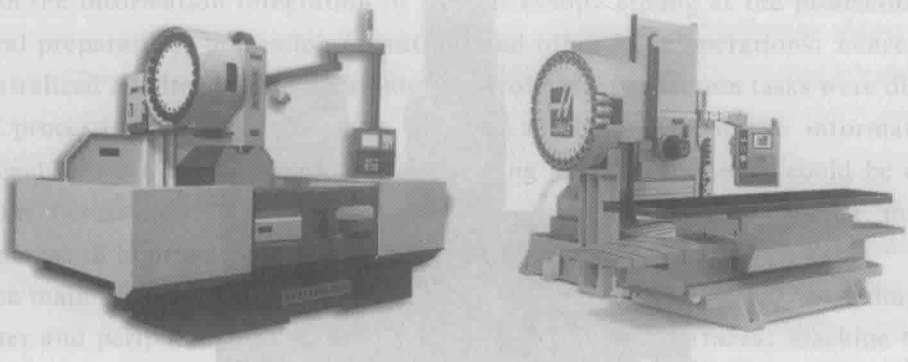
CNC milling machines（see Figure 1-5）can process three-dimensional complex surface. They are widely used in the automotive，aerospace（航空航天 háng kōng háng tiān），mold（模具 mú jù）and other industries. They can be divided into vertical CNC milling machines，horizontal CNC milling machines，duplicating CNC milling machines.

3. Machining centers（加工中心 jiā gōng zhōng xīn）

The machining center（see Figure 1-6）results from the development of CNC machine tools，generally considered machining centers for the CNC boring and milling machines with an automatic tool controller（ATC）. Machining center can do milling（铣削 xǐ xuē），

Figure 1-5 CNC milling machine

boring, drilling, broaching, fraising, tapping and other processing. Machining centers are classified as vertical ones and horizontal ones. The former ones' spindle axes are vertical, the latter ones' spindle axes are horizontal. The horizontal machining center is particularly used to machine the large, boxy and heavy workpieces.



(a) (b)

Figure 1-6 Machining center

(a) Vertical machining center; (b) Horizontal machining center

shù kòng zuān chuáng

4. CNC drilling machines（数控钻床）

CNC drilling machines (see Figure 1-7) can be divided into vertical ones and horizontal ones. Both of them mainly used for drilling（钻削 zuān xuē）and tapping, but also for simple milling.

5. CNC grinding machines (数控磨床 shù kòng mó chuáng)

CNC grinding machines are mainly used to machine hard surfaces with high precision. They can be classified as CNC surface grinders, inner cylinder grinding machines, contour grinding machines and so on. With the development of the automatic grinding wheel compensation technology, automatic grinding wheel(自动砂轮 zì dòng shā lún) dressing technology and grinding fixed cycle technology, CNC grinding function becomes increasingly strong.

Figure 1-7 CNC drilling machine

6. CNC electrical discharge machines(EDM) (数控电火花机床 shù kòng diàn huǒ huā jī chuáng)

CNC EDM is a special processing method, which makes use of discharge phenomenon with two different polarities of the electrode in the insulating liquid(绝缘液体 jué yuán yè tǐ), and can remove the material and then complete the processing. It has special advantages for the complex-shape molds and difficult-to-machine materials as shown in Figure 1-8.

Figure 1-8 CNC EDM

7. CNC wire-cut electrical discharge machines (WEDM) (线切割机床 xiàn qiē gē jī chuáng)

The working principle of CNC WEDM is similar to CNC EDM's, the only difference is that the wire electrode replaces the electrode.

## 1.5 The development of machinery manufacturing systems

With the continuous improvement of automation of CNC machine tools, the automated manufacturing systems based on CNC machine tools have become the key in the industrialized countries.

1. DNC system

The earliest definition of DNC referred to direct NC, which was researched in the 1960s. At that time, NC systems were expensive and punch tapes were easy to be broken, so the DNC systems were just some NC devices directly connected to a central computer, which was used to manage and transfer NC programs.

Since the 1970s, with the continuous development of CNC technology, the storage capacity and calculation speed of CNC systems had been greatly improved. The meaning of DNC was reformed from the simple direct NC to distributed NC. It not only includes all the functions of direct NC, but also has other advanced functions, such as the system information collection, system status monitoring, system control, and so on.

Since the 1980s, with the rapid development of the computer and communication technology, the meaning and functions of DNC had been widely expanding. Compared to the DNC system in the 1960s and 1970s, the new generation of DNC systems began to focus on the information integration of the workshop, aiming at the production plans, technical preparation, processing operations and other basic operations, hence realized the centralized monitoring and distributed control. The production tasks were dispatched to the processing units through the local area network, and the information was exchanged between them. The material handling and other systems could be extended condition permitting, thus it was not only suitable for the existing production environment to improve productivity, but also saved costs.

The main components of a DNC system are showed in Figure 1-9, including central computer and peripheral storage devices, communication interfaces, machine tools and machine controllers. The central computer is employed for data management, which transfers the machining programs from the large-capacity memory to the machine tools. The bidirectional information flow is controlled to dispatch data among multiple computers in order to achieve individual processing of each machine controllers. Finally, the central computer monitors and handles the feedback information from the machine tools. The information exchange and interconnections are the key issue for the DNC system. The main difference between DNC and FMS (flexible manufacturing system) is that there is no automated material handling system in the DNC, which makes it low cost and easy to implement.

DNC is suitable for multiple CNC machine tools, usually 4—6 or more and the manufacturing environment with NC program management problems (NC programs are too large for the CNC to storage, or the CNC requires changing programs frequently in machining, etc.).

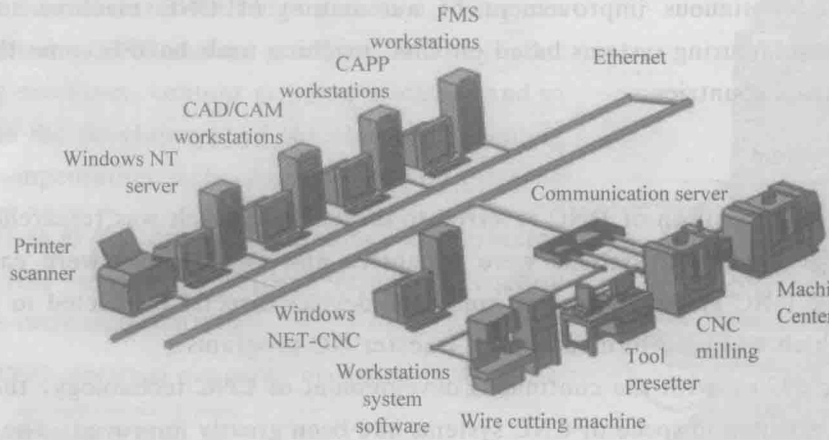



**Figure 1-9 Workshop DNC model**

2. Flexible manufacturing system (FMS)

According to the military standard of China, "the FMS is an automated manufacturing system which includes CNC machining equipment, material transportation devices and computer control system. It includes several flexible manufacturing cells (FMC) to achieve rapid reconfigure according to the change of manufacturing tasks or the production environment, which is suitable for multi-type, small and medium-volume production." In short, FMS is an automated manufacturing system composed of a number of CNC devices, material handling devices and computer control systems, and can be rapidly adjusted according to the manufacturing tasks and changes in the production type. At present, the most commonly seen FMS configuration includes four or more automatic CNC machine tools (machining centers and turning centers, etc.) connected by the centralized information control system and material handling system, which can achieve multi-type, small and medium batch processing and management without stopping.

FMC is the smallest scale FMS, which is the result of the development of FMS towards low-cost and small size. It has one or a small number of machining centers, industrial robots, CNC machine tools and material handling devices. The FMC has independent automatic processing functions, and also some automatic transport, monitoring and management functions, which can achieve some specific multi-type small-batch processing. Some FMCs have also achieved 24 hours unmanned running. It is more suitable for the small and medium companies with limited financial resources. Nowadays, many of the manufacturers have focused on the development of FMCs.

A flexible manufacturing factory (FMF) integrates a number of FMSs together with an automated multi-layer warehouse, and uses a computer system for communication, which contains the ordering, design, processing, assembling, inspection and delivery functions to form a complete FMS. It includes CAD/CAM, and makes the computer integrated manufacturing system (CIMS) into reality, to achieve the flexibility and automation for the production system, and then to carry out the production management, product processing and material handling in the factory scope. FMF is the highest level of automated production, reflecting the most advanced automation technology in the world, and also provides the basis for the realization of CIMS.

In order to ensure the continuous operation of the FMS, the cutting tools and the cutting process must be monitored. The possible methods include metering the output current, power or torque of the spindle motor; monitoring the signals of the tool breaking with sensors; directly measuring the changes in the cutting tool blade or workpiece size with a probe; accumulating the cutting time of the cutting tool for tool life management. In addition, the contact probe can be used to measure the thermal deformation of the machine tools and the installation error of the workpiece, and compensate the error accordingly.

3. Computer-integrated manufacturing system (CIMS) (计算机集成制造系统 jì suàn jī jí chéng zhì zào xì tǒng)

In 1974, Dr. Joseph Harrington firstly pointed out the concept of computer-integrated manufacturing (CIM) in the book titled "Computer-Integrated Manufacturing": a system based on the computer integrated manufacturing is called a CIMS. CIM is a philosophy or a guiding principle for organizing modern productions, and CIMS is the realization of this philosophy. The core content of CIM is, using the computer hardware, network and database technology, to integrate the business operation, management, planning, product design, manufacturing, sales and service departments, and the people, financial and material, in order to achieve high efficiency, high quality and high flexibility of the management, hence improve the competitiveness of enterprises. It focuses on solving the problems of system information integration in product design and business management, which combines the information technology, management technology and manufacturing technology for shortening product design, development, and manufacturing cycle, and achieving better adaption to the diversified market demands.

The entire production process is essentially about data collection, transfer and processing. The final product can be seen as the material representation of the computer data.

CIMS consists of four functional subsystems:

(1) Management information subsystem (MIS): Support the production planning and control, sales, purchasing, warehousing, accounting and other functions, and