Design and Implement a Micro Assembly Machine for Mechanical Watch Movements

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Abstract

Micro assembly refers to assembly parts with sizes ranging from micrometers to millimeters. Typical applications of micro assembly include microelectronics, sensors and actuators, MEMS devices, jewelries and mechanical watch movements.

There are some unique micro assembly problems difficult to solve, such as accuracy positioning (in micrometer range), high speed (acceleration in several gs), work piece pick and place (in milligram range), as well as quality (reliability and consistency). This thesis presents a new micro assembly workstation. The workstation consists of three parts: (a) a 3 axes positioning system (the X and Y-axes are driven by linear motors and the Z axis is driven by a servomotor); (b) a control system and (c) a computer vision system. This thesis focuses on the design and implementation of these systems.

Presently, the micro assembly workstation has been completed. As an application example, it is used to assemble ruby bearings (jewels) onto the main plates of mechanical watch movements. The operation procedure is as follows:

(a) Detect the exact bearing hole positions of the main plate using the computer vision system;

(b) Detect the position of the ruby bearing using the computer vision system;

(c) Pick up the ruby bearing by means of liquid adhesive force;

(d) Press the ruby bearing onto the bearing hole of the main plate; and

(e) Inspect the assembly quality using the computer vision system.

The position accuracy of the micro assembly workstation is ± 1.9 μm based on the experimental results. The time required assembling five ruby bearings (number of ruby bearings on one main plate) is one minute.

It is expected that the presented micro assembly workstation will find many applications from various industries in the near future.

摘要

微封裝是指介於微米與毫米級之間的封裝。微封裝技術主要應用在微電子學，感測器與執行機構，MEMS 設備，珠寶以及機械手表中。

微封裝過程中有一些具體的問題需要著重考慮，比如：位置精度（微米級），高速（幾個重力的加速度），抓取與安裝微輕配件（毫克級），還有裝配效果（重複性，持續性）。這篇論文介紹了一種新型的微封裝生產中心。該微封裝生產中心包括三部分：(a)三軸運動系統(X，Y 軸由直線馬達驅動，Z 軸由旋轉伺服馬達驅動)；(b) 控制系統；(c) 視覺回饋系統。這篇論文集中討論了控制系統和視覺系統的設計與運行。

目前，該微封裝中心已經完成。作爲一個應用的方向，該中心現在已被用來裝配機械式手錶的珠寶軸承。裝配過程可以概括爲：

(a) 用視覺系統中找到與特定珠寶軸承相應的孔洞位置。

(b) 用在視覺系統中找到珠寶軸承的位置。

(c) 利用液體表面黏附力將珠寶軸承抓起。

(d) 將珠寶軸承壓裝在相應的孔洞位置。

(e) 用在視覺系統檢查裝配品質。

實驗結果表明，該封裝機的位置精度達到了± 1.9 微米。安裝一隻機械手表主板上的五個珠

寶軸承需要的時間是一分鐘。

在不久的將來，該封裝中心將被開發出更多的工業用途。

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1. Introduction

Micro assembly refers to the assembly of miniature parts of typically millimeter and sub-millimeter size. Micro assembly has become an important area of research and development due to the ever-increasing demand for the miniaturization of commercial and domestic products, such as microelectronics, micro-mechanical systems, and micro electrical-mechanical systems (MEMS). Although many articles and papers have been published on micro assembly technology, there are a few commercially available micro assembly machines, and even fewer that are applicable to the assembly of mechanical watch movements. In the project reported in this thesis, we designed and implemented a unique micro assembly machine to assemble mechanical watch movements.

1.1. Literature Review

There is much research on micro assembly. Although Bohringer [1] provided a general overview of micro assembly, most of the research focuses on specific issues. For example, Kasaya [2] developed an automated assembly operation by using visual and force control, and Keller [3] developed Hexsil micro-grippers that utilized integrated actuators and strain gauges for force feedback control. Zhou [4] developed a micro-gripper and micro-gripping strategies by using optical beam deflection techniques. Carrozza and *et al.* [5] built a LIGA (a German acronym for "**Li**thographie, **G**alvanoformung, **A**bformung," in English (X-ray) Lithography, Electroplating) micro-gripper with integrated semiconductor strain gauges, and Nelson and *et al.* [6] described the use of vision-based feedback in the assembly process. Other work has investigated the use of virtual reality (VR) based simulation [2, 7], visual serving [6], and force sensing [8, 9].

Yang, Gaines, and Nelson [10] developed an experimental micro assembly work cell for the efficient and reliable 3D assembly of large numbers of micro-machined thin metal parts into micro-machined holes in 4-inch silicon wafers. The work cell consists of a multiple-view imaging system, a 4 Degree Of Freedom (DOF) micromanipulator with high-resolution rotation control, a flexible micro-gripper, and a control system. They also developed a piezoelectric force-sensing unit that integrates with the manipulator system to enhance pickup reliability.

Huang and *et al.* [11] presented a piezoelectric micro-gripper with a dual-cantilever structure that can judge whether an object has been clamped and how much force it has suffered from a strain signal at the root of the micro gripper (see Figure 1-1). The micro-force sensor ensures that the micro objects are not forced to deformation or even destruction. Huang *et al.* analyzed a piezoelectric bimorph model and its displacement-voltage and force-strain relationships, and showed that the gripper was able to complete the micro assembly tasks. However, as the apparatus is a gripper rather than a machine, it can be used only in a limited number of applications because it can only nip objects.

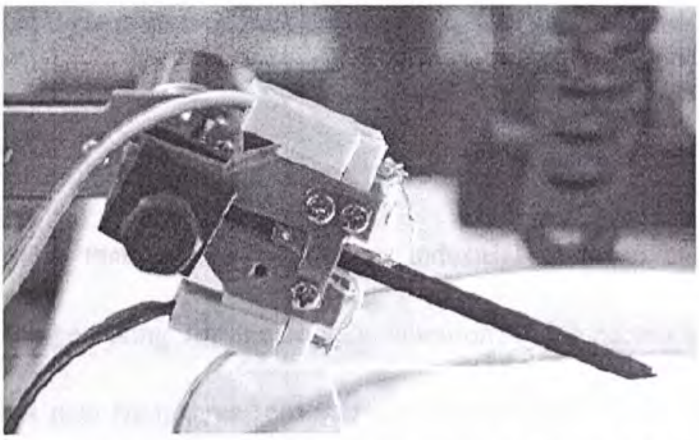


Figure 1-1 Photograph of the micro-gripper of Huang *et al.* [11]

Boettner, Cecil, and Jiao [12] highlighted that Micro Device Assembly (MDA) is an emerging area of importance, and that the design of advanced collaborative frameworks is crucial to support the rapid assembly of micro devices. They discussed the implementation of such frameworks and described the use of information models and virtual models, and then proposed and implemented various assembly approaches and physical activities. Virtual prototyping and simulation analysis were conducted before the physical assembly tasks were implemented. The authors also presented a software module structure that works collaboratively in micro assembly applications.

Udeshi and Tsui [13] described a robust algorithm for planning assembly sequences for open-loop micro assembly. The algorithm detects any collisions that may occur when executing an assembly sequence, and automatically modifies the assembly sequence to avoid such collisions. The algorithm has a low time complexity and is guaranteed to find a collision-free sequence if one exists. It can also be extended to generate an optimum assembly sequence. However, the system is not close-loop, which means that there is no feed back response.

Robl and Farber in [14] reported a new 2 DOF precision gripper tool with a micro positioning system that enables a standard industrial robot to carry out micro assembly by compensating for the robot's vibration and inaccuracies. Its control system combines data from three sensors by means of signal level sensor fusion to correct the position errors. The control system consists of two closed-loop regulators and one open-loop regulator. The sensor data is synchronized to the control sample rate with a linear first-order extrapolation, after which the data is fused with a Kalman filter. The realized control system reduces vibration to less than 30%, and the position accuracy without disturbances is better than 2 microns according to experimental results. The use of sensor fusion simplifies the multi-sensor control design compared with approaches without sensor fusion.

Precise micromanipulation to achieve accurate alignment is one of the principal challenges in the assembly of miniature electronic or optic devices. Normally, the mechanical misalignment of these precision devices is only noted when the device functionality fails. Ryu and *et al.* [15] developed an efficient tool for the identification and correction of the alignment problem. As the corrective activity of miniature devices is usually accompanied by some level of plastic deformation, a proper identification of force and deformation during operation is essential. In addition, most devices have a very dense population of tiny parts that are spread and arranged on a two-dimensional surface, and thus maintaining accessibility with a clear path during the corrective operation is not straightforward. Figure 1-2 shows the system designed by Ryu *et al.*

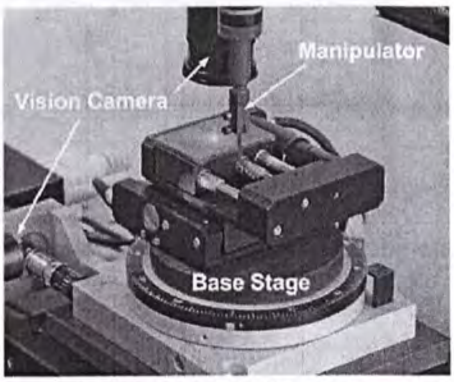


Figure 1-2 Micro manipulation system [15]

Chang and *et al.* [16] reported the design, implementation, and testing of a visual control micro assembly system. By employing certain design axioms, the authors efficiently and successfully developed a micro assembly system that satisfies the Functional Requirements (FRs). The system consists of a 754 × 477 × 100 μm PolyUrethane (PU) micro gripper actuated by an SMA actuator for gripping, transporting, and adhesive bonding operations. The arc-shape Shape Memory Alloy (SMA) actuator has a residual stress that functions as a biased spring for accurate and efficient operation. In performance tests, a 20 μm diameter metal wire was gripped, transported, glued, and assembled to a 380-μm metal wire under visual control (shown in Figure 1-3). However, in operation, the working environment has to be enclosed and isolated to avoid environmental effect on the operation of the micro gripper.

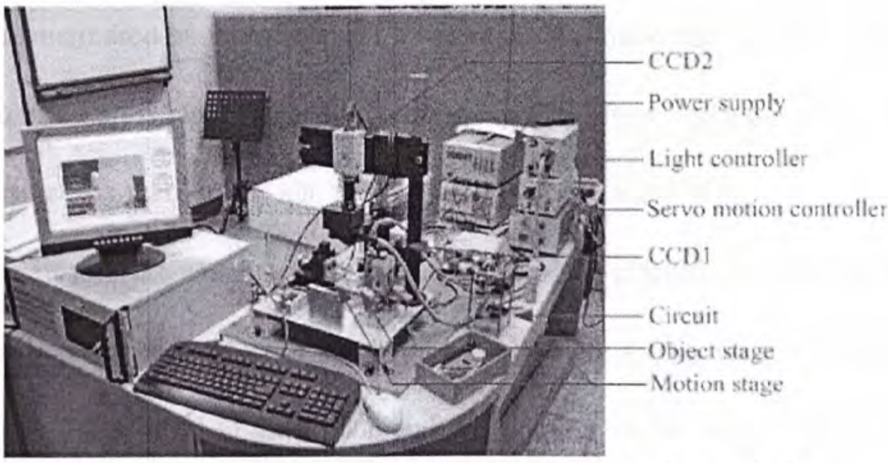
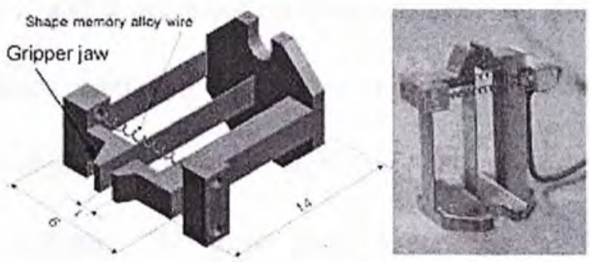


Figure 1-3 Micro assembly system of Chang and *et al.* [16]

Yeh *et al.* [17] used micro resistance welding to assemble micro Ni structures with electro-thermal micro actuators. As the point of contact between the two structures has a large contact resistance, a high local temperature can be generated and a current can occur due to joule heating. To move the microstructure and provide welding pressure to generate proper contact resistance between the two microstructures, they used bent-beam electro-thermal actuators, and by properly designing the size and number of actuators identified the feasible operation parameters for contact resistance and pressure. The authors showed that micro-resistance welding can be achieved with a contact resistance of 4.6Ω to 12Ω at a contact pressure of between 7.2 and 39.3 MPa.

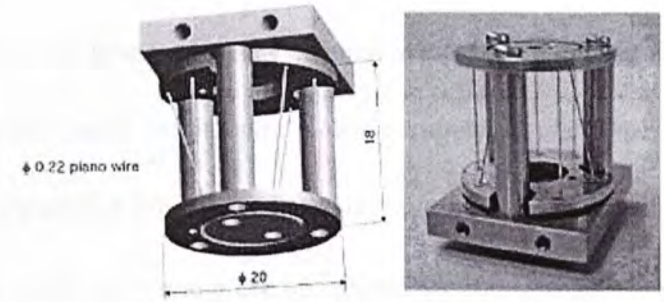
Tanikawa, Hashimoto, and Arai [18] reported a micromanipulation system that consists of a micro-hand that manipulates microscopic objects and a bonding system that glues the micro parts together. An adhesive bonding technique for the assembly of microscopic parts was also proposed. The capillary phenomenon was applied to obtain a micro drop of adhesive agent smaller than the micro parts. A glass fiber was inserted into a glass pipette to obtain a strong capillary effect, and a measured amount of adhesive was then drawn into the pipette. Finally, a micro drop was obtained by applying air pressure without control from the end of the pipette. Using this technique, a micro drop with a diameter of just 2 μm was obtained. As the relationship between the length of the liquid in the pipette and the diameter of the micro drop is almost linear, the micro drop size can be easily controlled. By using this bonding technique and the two-fingered micro hand, the authors assembled a three-dimensional microscopic structure "micro scarecrow." The combination of this micro manipulation system with the new adhesive application technique allows microscopic structures of various shapes to be assembled.

Bang and *et al.* in [19] presented a new micro assembly system that is composed of a micro gripper, a micro Remote Center Compliance (RCC) unit, a voice coil motor-driving mechanism, and precision motion stages. The micro gripper is 1 mm in length. The micro RCC unit has a low translational and rotational stiffness sufficient for micro part assembly. The voice coil motor-driving mechanism can generate linear motion with an adjustable stiffness, and can also measure external force in the direction of motion. Figure 1-4 and Figure 1-5 show the gripper and the RCC unit, respectively.



(a) (b)

Figure 1-4 Micro gripper actuated by two Shape Memory Alloy (SMA) coils [19]



(a) (b)

Figure 1-5 Micro RCC units [19]

Lee and *et al.* [20] developed a multiple-magnification image-based micro-positioning system and its architecture. Micro images have different characteristics from macro images, and offer more precise information about micro objects. The vast visual information contained within such images raises the possibility of vision-based micro positioning. However, certain information is redundant for object recognition in micro-positioning systems, and the high enlargement ratio of optical microscopes limits the field of view, although multiple-magnification-based micro vision systems solve this problem. Micro-positioning operations for micro assembly are divided into two parts: micro positioning of the vertical micro stage for auto focusing and micro positioning for the X and Y micro stages. However, there are still many problems to be solved before micro positioning can be used to handle micro objects. For example, a more precise object recognition algorithm and the development of an image-processing algorithm for micro image processing are both needed. The different heights and overlapping of the micro object and the micro gripper also have an influence on vision-based micro positioning systems and micromanipulation.

Chen and Huang [21] proposed a new vacuum gripper for handling micro targets that has a two-layered control architecture with a computer as the upper layer controller and an Micro Controller Unit (MCU) as the bottom layer controller. The device is able to carry out pick, hold, and place operations for 100-0 to 300-μm sized targets. A fuzzy PD-based controller was also designed to control the working pressure, the satisfactory performance of which was validated by simulation experiments. However, the gripper's application is limited, as it can only operate with targets of between 100 and 300 μm.

Strijp, Langen, and Onosato [22] investigated the use of adhesive forces and the dominant interactions in micro assembly, and found that volumetric forces have a smaller or negligible influence. The influence of the van der Waals force is negligible for separations larger than 100 nm and has a small effect on objects in micro assembly. The electrostatic force is the most important force, but only when the capillary force can be avoided. The capillary force is found to dominate all other forces at the micro scale. A dry or vacuum environment that eliminates this force has been suggested and assumed for further analysis, but this gives rise to onerous environmental requirements.

Cecil and Trivedi [23] provided an overview of two components (the virtual reality environment and the path planning modules) in the development of an Information-Based Manufacturing (INBM) framework for Micro Device Assembly (MDA). These components can be viewed as software resources in a virtual enterprise for micro assembly. The other resources in the virtual enterprise scenario include additional software tools and physical resources. To mimic the modeled scenario, the virtual assembly environment, Enterprise level Task Manager (ETM), and path planning modules were hosted on various computers linked via the Internet. A second micro assembly work cell is under development to increase the scope of the micro assembly capabilities. However, there is a need for future research that focuses on developing additional criteria for comparing the plans generated by various software entities in a virtual enterprise (such as cost and interface compatibility).

1.2. Project Background

A Mechanical watch movement has a complicated structure and many parts of it are in the range of millimeter. The Hong Kong Watch Manufactures Association, Federation of Hong Kong Watch Industry and Trade and Hong Kong Innovation and Technology Commission support a project in our unit. The aim of this project is to develop advanced technologies and capability for design and build high-quality mechanical watch movements and other precision engineering parts.

Thus far in the project, we have improved many of the parts of mechanical watch movements, and are testing whether these enhanced parts improve the mechanical watch movement, which will determine whether the improvements are suitable or not. Although, as the previous section demonstrates, there is much research on micro assembly, little work has been conducted on mechanical watch movements. As the dimensions of the mechanical parts of watch movements are in millimeters, they are hard to assemble. To avoid the negative impact of man-made factors during assembly, there is a need to design and implement an assembly machine for assembling mechanical watch movements.

We have developed a machine to assemble the ruby bearings of the main plate of watches, which are important components in mechanical watch movements. Figure 1-6 shows that a mechanical watch movement is made of over 100 miniature parts, including pinions, wheels, and ruby bearings. As shown in the figure, in mechanical watch movements ruby bearings act as bridges that connect other watch parts with the main plate. This means that if the ruby bearings are not suitably assembled, then the whole watch will not work fluently or may not even work at all.

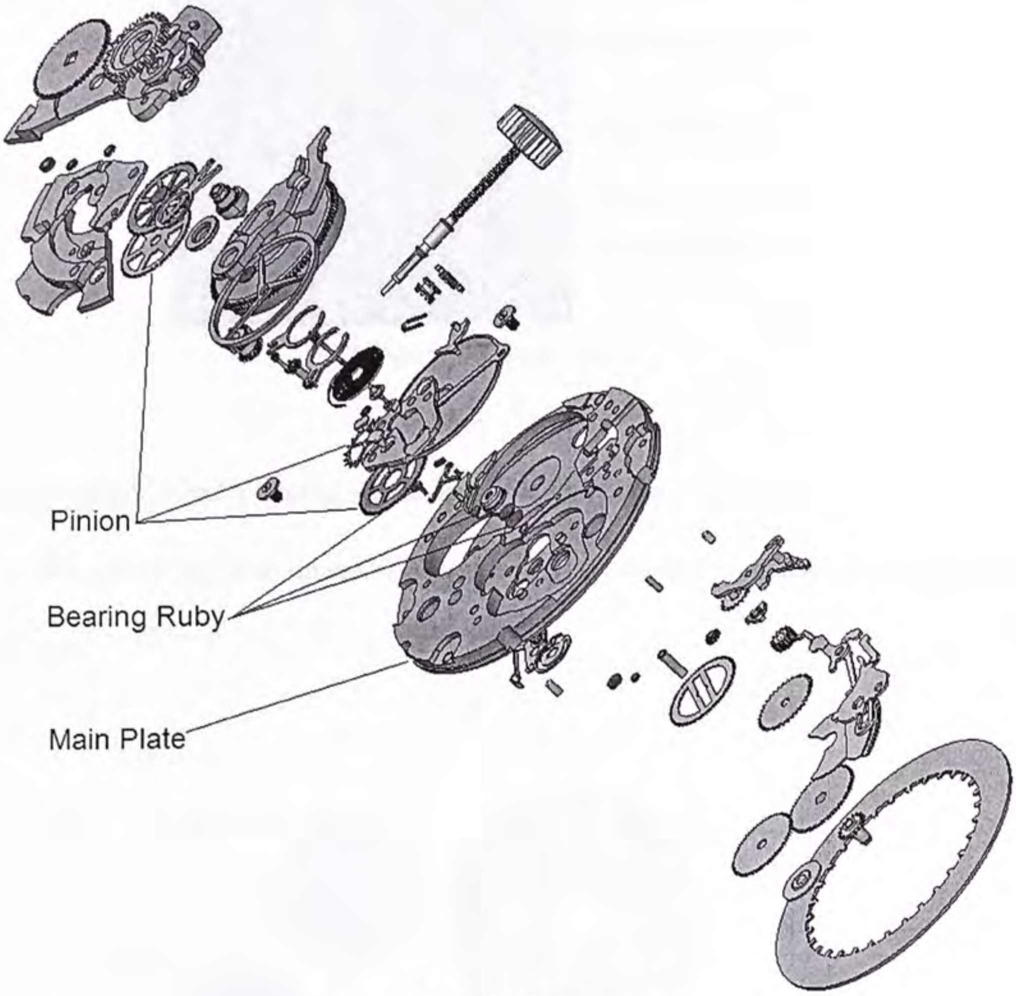


Figure 1-6 Watch Structure

Figure 1-7 shows a more detailed photo of the main plate of a watch, which is the base that holds the other parts of the movement. It can be seen that the pallet wheel pinion is connected to the main plate through the pallet wheel ruby bearing, which is assembled in the pallet wheel hole on the main plate. The micro assembly machine presented in this thesis functions to assemble such ruby bearings into the corresponding bearing holes on the main plate.

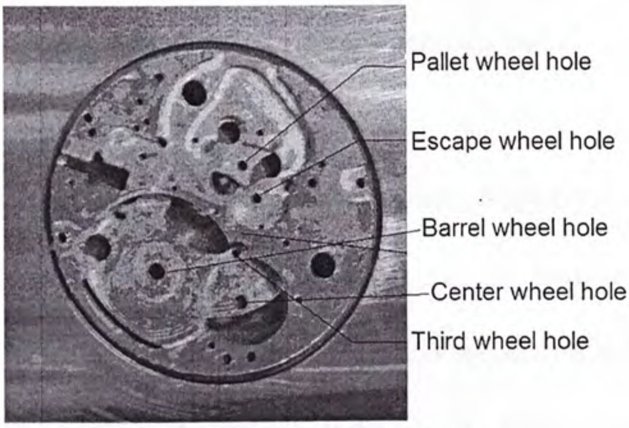


Figure 1-7 Main Plate

The five kinds of ruby bearings to be assembled on the main plate are shown in Figure 1-8 (magnified by 438 times), and Table 1-1 shows the dimensions of the ruby bearings.

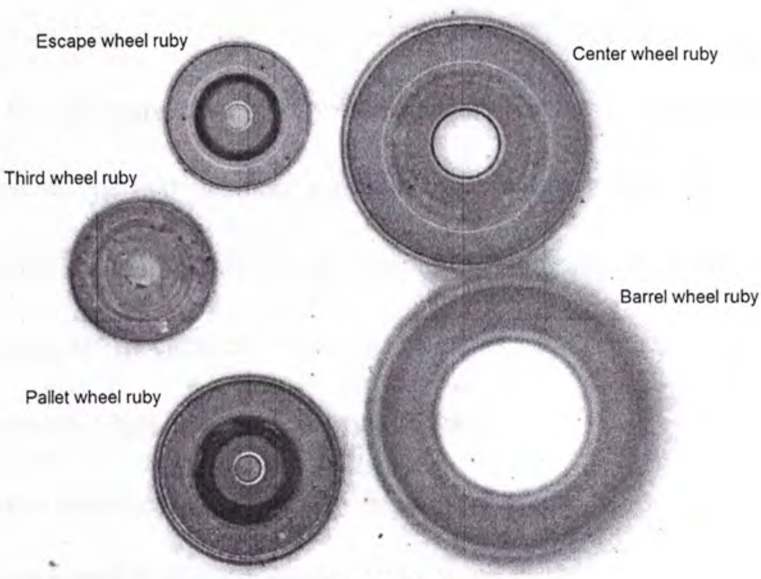


Figure 1-8 Ruby Bearings

Ruby	Barrel arbor ruby	Center wheel ruby	Escape wheel ruby	Third wheel ruby	Pallet fork ruby
Outer diameter of rubies	1.40377	1.20534	0.90362	0.70239	0.90528
Inner diameter of rubies	0.69753	0.29897	0.10166	0.16192	0.10204
Height of rubies	0.4	0.3	0.19	0.21	0.18

Table 1-1 Sizes of ruby bearings (mm)

There are two critical requirements for the successful assembly of the ruby bearings: the first is the depth of the ruby bearings relative to the bearing holes on the main plate, which affects the height of the pinions; and the second is the gradient of the ruby bearings, which affects the flatness of the pinions. These two requirements must be met to ensure that the neighboring pinions are meshed; otherwise, the movement will not work fluently or may not work at all.

1.3. Objectives

Based on the literature review, it would appear that most existing research work concentrates on one part of micro assembly, such as the gripper or the control, and that few of the existing machines are suitable for the assembly of micro-mechanical systems such as mechanical watch movements. In general, micro-mechanical assembly systems must have the following features.

1. A high position accuracy (typically in the range of μm).
2. Sufficient assembly force (typically in the range N).

3. A high speed (typically, 3.6 m/s and 1 m/s^2).

The objective of the research is to design and build a micro assembly machine that can assemble many kinds of micro mechanical parts. Presently, the assembly machine has been built. As a first step, it assembles five different ruby bearings (the third wheel ruby bearing, the pallet wheel ruby bearing, the escape wheel ruby bearing, the center wheel ruby bearing and the barrel wheel ruby bearing) onto the watch main plate of a mechanical movement at the speed of 3.6 m/s with a success rate higher than 99%.

This thesis presents our micro assembly machine, which can be used to assemble various micro-mechanical systems, although presently it is specialized for the assembly of ruby bearings on the main plate of mechanical watch movements. The remainder of the thesis is organized as follows. Chapter 2 describes the design of the machine. Chapter 3 discusses the implementation of the machine in terms of both the hardware and the software module. Chapter 4 presents the experimental results. Finally, Chapter 5 gives some conclusions and details future work.

2. Design of the micro assembly machine

Our micro assembly machine is designed to assemble mechanical parts that are of a millimeter and sub-millimeter size. Currently, the micro assembly machine is set up for the assembly of ruby bearings in mechanical watches, but can be expanded to other applications in the future.

This chapter presents the design of the micro assembly machine. It first details the aspects that need to be met by micro assembly machines for mechanical watch movements. Hardware has been chosen based on these requirements and the objectives listed in Chapter 1, namely, a high position accuracy (typically in the range of μm), sufficient assembly force (typically in the range of N), and a high speed, typically, 3.6 m/s and 1 m/s^2). Mechanically, the machine consists of an actuating system, a control system, and a computer vision system. One of the keys to the success of the assembly process is the gripper. This is discussed in detail in this chapter, and a new micro assembly force is introduced.

2.1. Aspects that need to be met

According to the literature review in Chapter 1, there are some aspects that micro assembly machines must meet. These micro assembly machines are not particularly designed for mechanical watch movements, so we develop a micro assembly which can be used for mechanical watch movement assembly. The design of the machine for watch assembly concentrates on improving the following two aspects.

a) Broad applications. Most micro assembly machines are designed to assemble only one kind of micro part. Our micro assembly machine is designed to be a multiple-purpose machine that can be used for many applications, such as the assembly of pinions and pillars in mechanical watch movements.

b) Low environmental requirement. To achieve a high accuracy, most micro assembly machines must be operated under particular environmental conditions, such as a constant temperature and constant humidity. In contrast, our micro assembly machine can complete demanding assembly tasks in a normal environment.

2.2. Hardware of the micro assembly machine

Figure 2-1 shows the hardware of the micro assembly machine, which consists of three main parts: the actuating system, the vision system, and the control system.

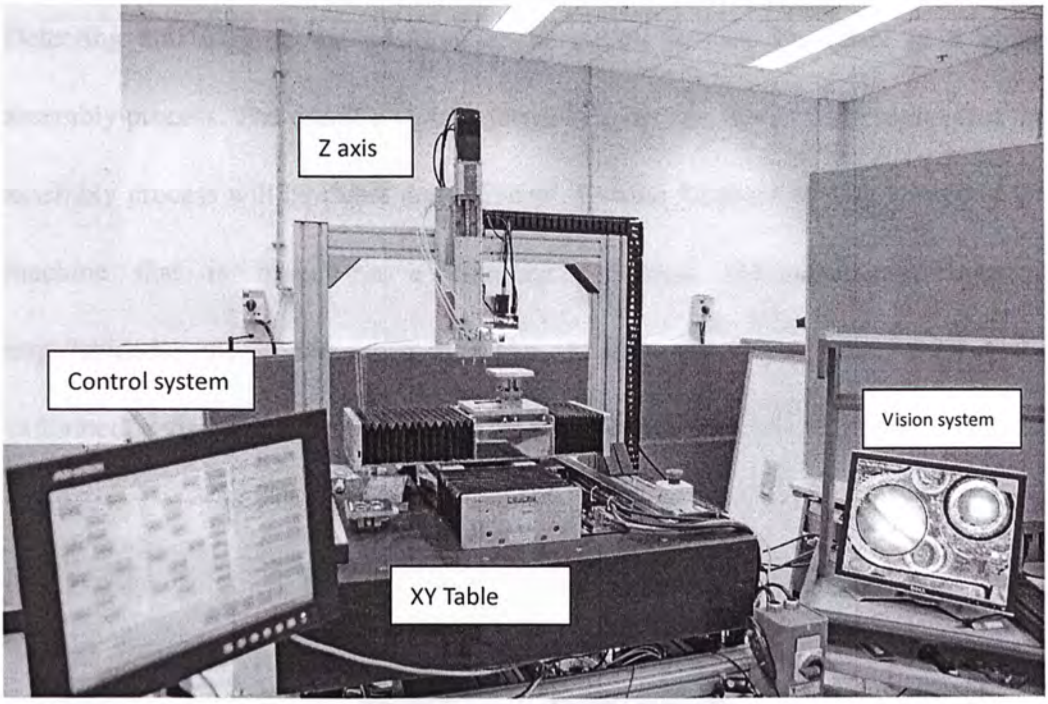


Figure 2-1 Micro assembly machine

The relationship between the three parts of the system can be summarized as follows. The vision system detects the targets and transfers information about the position of the targets to the control system. The control system commands the actuating system to complete the assembly tasks, and the actuating system and the vision system work collaboratively under the command of the control system to perform the assembly tasks. If the whole machine were a human being, then the control system would be the brain, the vision system the eye, and the actuating system the hand.

2.2.1. The vision system

Detecting and logging the position of the targets is very important in a micro assembly process. The use of a vision system to undertake these tasks ensures that the assembly process will be fluent and efficient. A vision feedback system is used in the machine that is based on a commercial system (Manufacturer: Keyence: http://china.keyence.com/company/asia.php, Model: CV-3000 Figure 2-2). Once calibrated, a vision resolution of 2 μm can be achieved.

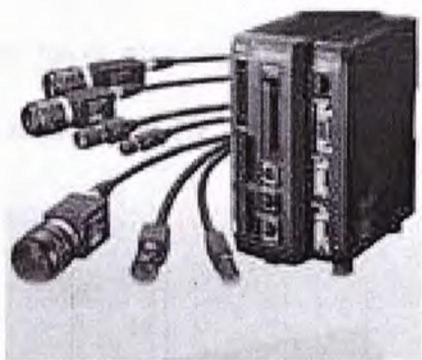


Figure 2-2 Keyence CV-3000 (http://china.keyence.com/company/asia.php)

2.2.2. The control system

The control system consists of a PC-based motion controller card and an industrial computer. The controller card is a low-level control system and is used to manipulate the actuating system. The industrial computer is a high-level system and acts as the decision-making center. The industrial computer controls the machine by commanding the actuating system and the vision system. The commands for the actuating system are transferred through the motion controller, whereas those for the vision system are transferred directly.

One computer-based motion controller card is used to manipulate the actuating system. The motion controller card is manufactured by the Chinese company Googoltech Technology Limited (http://www.googoltech.com.cn/web/chi/main.jsp) and the model number is GT-400-SV (Figure 2-3). Each card is capable of controlling up to four axes during independent motion and up to three axes during coordinated motion. Typically, in the micro assembly machine the controller card is used to control three axes and a handy pulse. The structure of the control system is shown in Figure 2-4.

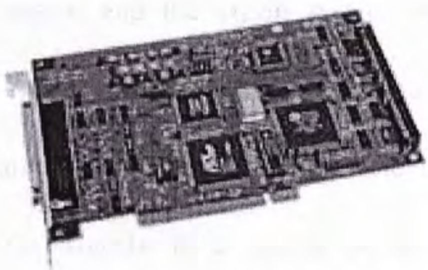


Figure 2-3 Motion controller

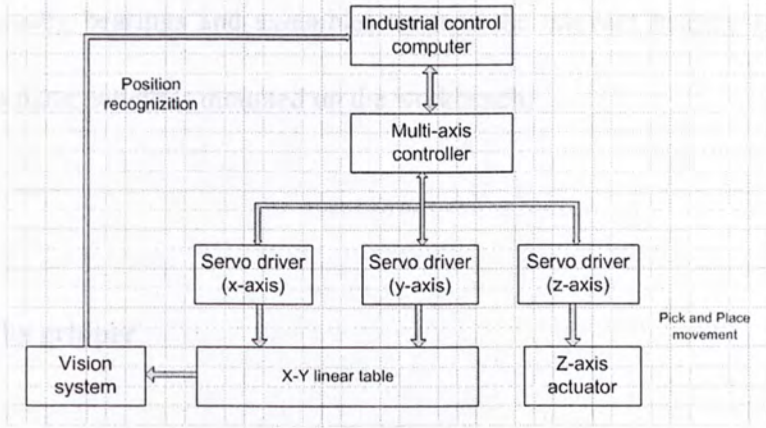


Figure 2-4 Control system

At the top level of control, the industrial computer acts as the decision-making center, and decodes the human operator's commands into c language script. This script is then decoded into analogue and numerical signals. Some of these signals are transferred to the multi-axis controller card and the rest are transferred to the vision system. The actuating system and the vision system work collaboratively. The controller card separates the signals transferred to the actuating system for different amplifiers, which then amplify the signals to stimulate the relevant motors. The method of separating the signals is a means of making the motors work collaboratively.

2.2.3. The Actuating System

The actuating system consists of three axes, a gripper, and a workbench. The three axes are used to position the gripper and workbench in the desired place. The gripper fetches the ruby bearings and assembles them in the relevant bearing holes on the watch main plate, which is mounted on the workbench.

2.2.3.1. The gripper

The gripper has a flexible structure, which allows the gripper heads to be changed to those most suitable for the assembly task. Three gripper heads are used for assembling the mechanical watch parts.

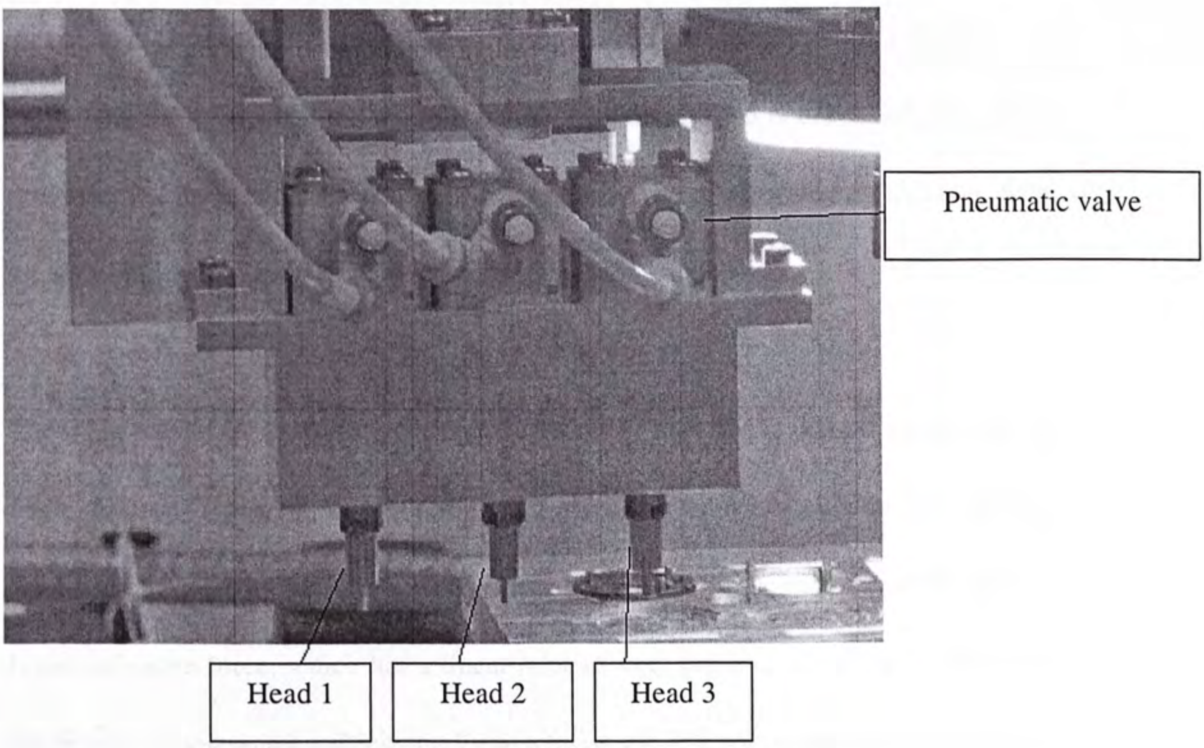


Figure 2-5 Gripper

As is shown in Figure 2-5, head one, head two, and head three pick up different ruby bearings separately. Each gripper head has a different cross section. According to the geometric properties of the heads (Table 1-1), head one is used for the assembly of the third wheel ruby bearing, the pallet wheel ruby bearing, and the escape wheel ruby bearing; head two is used for the center wheel ruby bearing; and head three is used for the barrel wheel ruby bearing. The working head is pushed downward by 5 mm by a pneumatic valve to avoid collision with the other heads during the assembly process.

The pneumatic valve that activates the working gripper head is supported by compressed air that is fed into the valve by a 0.7 MPa air pump. The diameter of the contact surface between the gripper head and the compressed air is 5 mm, which means that the maximal force that the gripper head can supply is 13.5 N. In other words, the limit force for the micro assembly machine is 13.5 N under 0.7 MPa of air pressure. If a larger force were needed in another type of assembly application, then the air pump would need to be replaced with a larger model.

The main reason for using three gripper heads rather than one is that the heads need to fetch different types of ruby bearings and avoid mechanical collision between the heads and the watch main plate. The gripper heads pick up the ruby bearings through liquid adhesive force, which has a linear relation with the area of the cross section of the heads. To guarantee sufficient adhesive force, the gripper heads thus need to have cross sections that match the particular size of ruby bearings that they are tasked with picking up. For example, head one's surface is too small to generate enough adhesive force to fetch barrel wheel ruby bearings, and head three's surface is too large to pick up the third wheel ruby bearing, the pallet wheel ruby bearing, and the escape wheel ruby bearing, which means that there would be a mechanical collision between head three and the watch main plate during assembly of these three bearings.

In micro assembly, to pick up a part, various types of forces can be employed, traditionally, including liquid surface tension force, electrostatic force, magnetic force, and pneumatic suction force. Each method has its advantages and limitations. For example, a magnetic force gripper can only be used for magnetism parts, large gripping forces may result in parts being damaged, and electronic parts may be damaged by electrostatic force. The most appropriate method depends on the part to be assembled, the environment, and the assembly requirements. Actually, there are two forces, the liquid surface tension and liquid adhesive force, have the most suitable characteristics for the mechanical watch movements assembly. A study of these forces is presented as follows.

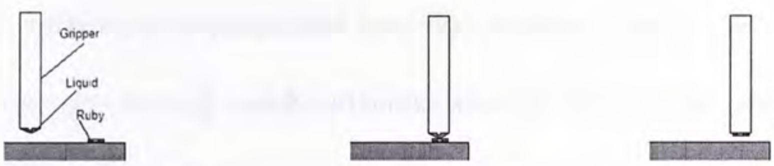
Where an electrostatic force is used, the material of the assembly components should have dielectric properties. However, a micro assembly machine may be designed for many applications, some of which are not dielectric, such as ruby bearings, and thus the use of this kind of force is not always appropriate.

Magnetic force is unsuitable for use in watch assembly because watch components must be kept away from magnetic objects.

A seemingly suitable force is suction force. When this force is used, the gripper usually consists of a thin tube or pipette connected to a vacuum pump, which is thus cheap to manufacture and easy to replace. The cycle time can also be maintained at well below 100 ms, and it is possible to release components by using a puff of air. This type of gripper force has applications for a wide range of materials, and will not alter the properties of the assembled components.

The main limitation of a suction gripper is mechanical collision between the gripper head and the component to be assembled. This leads to high levels of collision and static forces during the pickup and placement of components, which may damage both the gripper head and the components. Another limitation is the possibility that small particles may obstruct the tube when handling certain kinds of porous materials. The presence of particles is a common issue during micro assembly using suction, which is why it is usually performed in a clean room environment [24]. However, such environmental requirements make the use of this force expensive compared with the selected method.

The liquid surface tension method has several advantages: it is free from magnetic noise, there is no electrostatic damage to the parts, and it has a large application domain. Because of these advantages, this force was used at the beginning of this project to pick up the components in the micro assembly machine. However, the performance of liquid surface tension systems is affected by environmental temperature, pressure, liquid density, purity, and other liquid characteristics. The process of picking up the ruby bearings and placing them into the corresponding bearing holes on the main plate using liquid surface tension is shown in Figure 2-6.



(a) (b) (c)

Figure 2-6 Illustration of the pick up action: (a) The gripper head is dipped into some liquid; (b) The gripper head moves to the ruby bearing location; (c) The gripper head picks up the ruby bearing using liquid surface tension.

However, several problems arise when this method is used in watch component assembly. The main drawbacks are as follows.

1 The hardware requirement is onerous, because a difference in z-axis as small as 0.01 mm can determine whether the gripper head is successful or fails. The working bound value is hard to control, because the volume of the liquid changes from time to time due to environmental factors.

2 The depth of the liquid pool that contains the liquid changes as a result of vaporization, causing the liquid volume on the gripper head to change. The liquid on the side surface of the gripper head, which will be part of the final liquid on the gripper head, changes with the depth of the liquid pool, which results in a

difference in the liquid volume on the gripper head. This causes the liquid surface tension to change and means that the previous gripper working bound may not work the next time around. The velocity of the gripper head also has a significant influence on the volume of the liquid. In summary, any factor that affects the volume of liquid on the gripper head will affect the result of the assembly.

3 Environmental conditions have a great effect on the assembly results. For example, different temperatures and humidity levels will change the volume of liquid on the gripper head, which will further alter the liquid surface tension.

4 To eliminate the effect of environmental conditions, a high density and low volatility liquid should be used, but the side effect is that the liquid surface tension becomes larger and the ruby bearings, especially the third wheel ruby bearing, will float on the surface. This makes it hard for the machine to locate the correct position for the ruby bearings when assembling them onto the main plate, and usually results in assembly failure.

The foregoing discussion demonstrates that there are no existing force types wholly suitable for our micro assembly machine. We have thus developed a new method, that of liquid adhesive force, for our particular assembly application, although it should also be applicable for use in other applications. The liquid used is SYNT-A-LUBE 9010, which is a kind of oil used in watches. The technical data of the liquid is given in Table 2-1 [25].

Technical Data	SYNT-A-LUBE 9010
viscosity at 0°C	625 cSt
viscosity at 20°C	150 cSt
viscosity at 50°C	31 cSt
surface tension at 25°C	33.8 dyn/cm
contact angle on ruby	22-25°
contact angle on steel	15-18°
density at 20°C	0.907
evaporation loss after 5 days at 100°C	0.50%
temperature range for usage	70°C--29°C

Table 2-1 Properties of SYNT-A-LUBE 9010[25]

This oil was chosen because it is one of the oils used in mechanical movements. It is easy to control the quantity because of the oil's low volatility and the environmental requirements are not onerous. Experiment results show that with the oil, the gripper can pick up objects whose mass is less than 10g.

During the pick up operation, the gripper head first dips into the oil pool to acquire some oil, which usually form a thin cover over the gripper head. Next, the gripper will move to the designed position to pick up the ruby bearing. The, the oil on the gripper head sticks the ruby bearing and picks it up. Based on our experiments, it is found that this method performs very well.

2.2.3.2. The three axes

The machine has three axes. The x axis and y axis are driven by Hiwin linear motors (Manufacturer: Hiwin: http://www.hiwin.com/, Model: LMS27), as shown in Figure

2-8, and have a resolution of 1 micron. The z axis is driven by a servomotor (Manufacturer: Mitsubishi: http://www.mitsubishi-motors.com/, Model: HF-KP43B), as shown in Figure 2-9. All three motors are driven by a Mitsubishi amplifier (Model: MR-J3-20A), which is also shown in Figure 2-9.

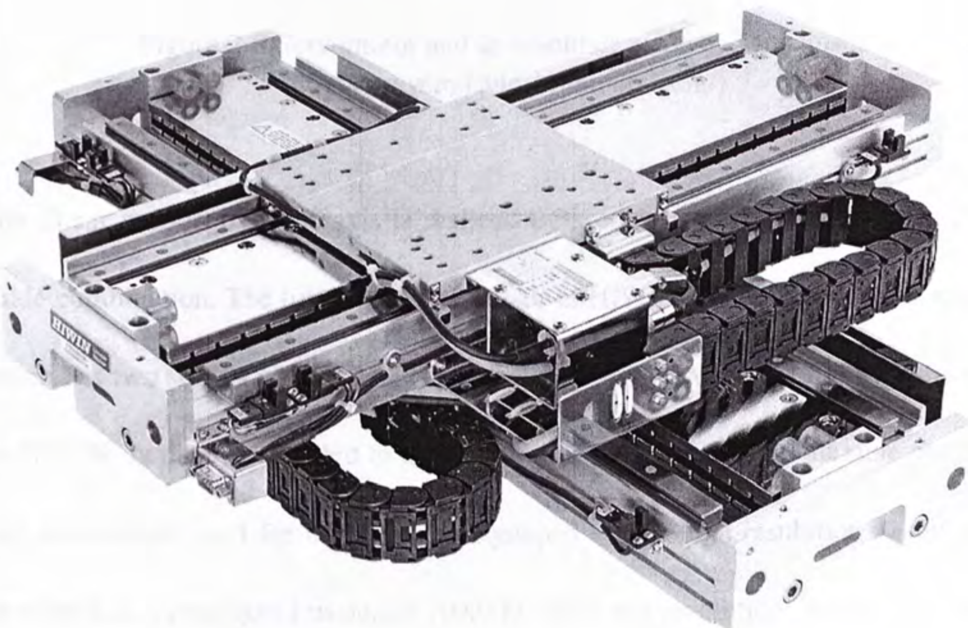


Figure 2-7 Linear motor driving the XY table made by Hiwin (http://www.hiwin.com/)

Figure 2-8 Servomotor and its amplifier made by Mitsubishi
(http://www.mitsubishi-motors.com/)

The linear motion of the z axis is realized by a conventional ball-screw and linear guide combination. The linear guide has a pair of HIWIN HGN20 linear rails, each of which has two sliding blocks. The FSV model ball-screw, which is also manufactured by HIWIN, is directly coupled to the servomotor via a DKN-series flexible coupling. The servomotor used for the z axis is equipped with a high-resolution 18-bit serial encoder that is configured to output 100,000 counts per revolution. As the pitch of the ball-screw is 1 cm, the resolution of the motion in the z axis direction is 0.1 μm. The ball-screw is properly preloaded so that backlash is guaranteed to be within 5 μm along the entire range.

The whole system is set up as a semi-closed loop system, which means that it is controlled based on feedback from the motor encoders.

2.2.3.3. The workbench

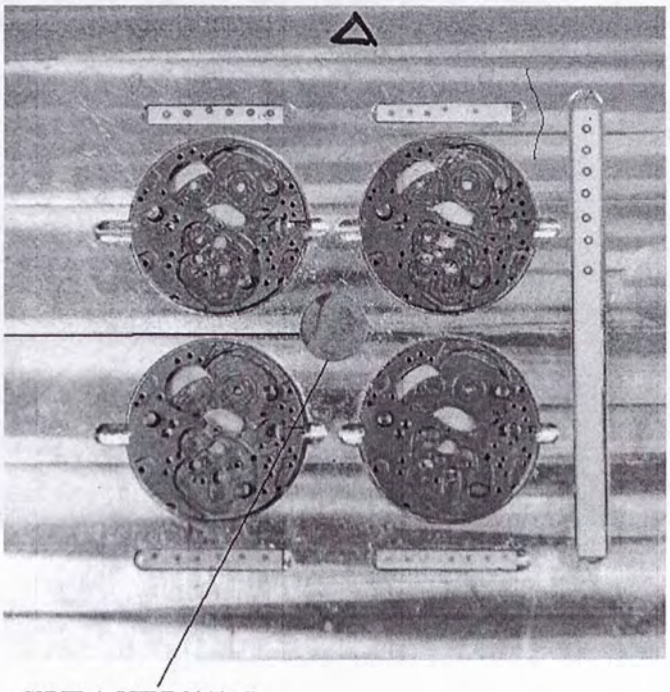


Figure 2-9 Materials mounted on the workbench

The ruby bearings and watch main plates are mounted on a workbench, which is set up on the x and y axes. As shown in Figure 2-10, the workbench carries the oil, ruby bearings, and four main plates. After assembly, the human operator must replace the assembled main plates with unassembled plates and add more ruby bearings if needed. Figure 2-11 shows the workbench, which is connected to the x and y axis through a pincer structure.

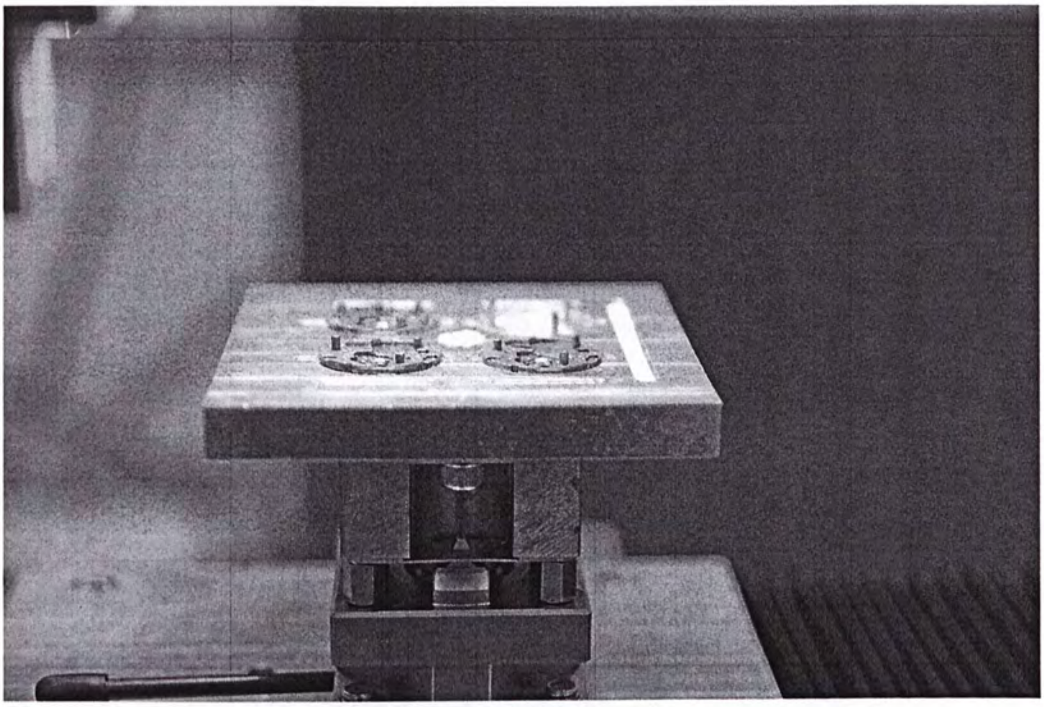


Figure 2-10 Workbench

2.2.4. The complete structure of the micro assembly machine

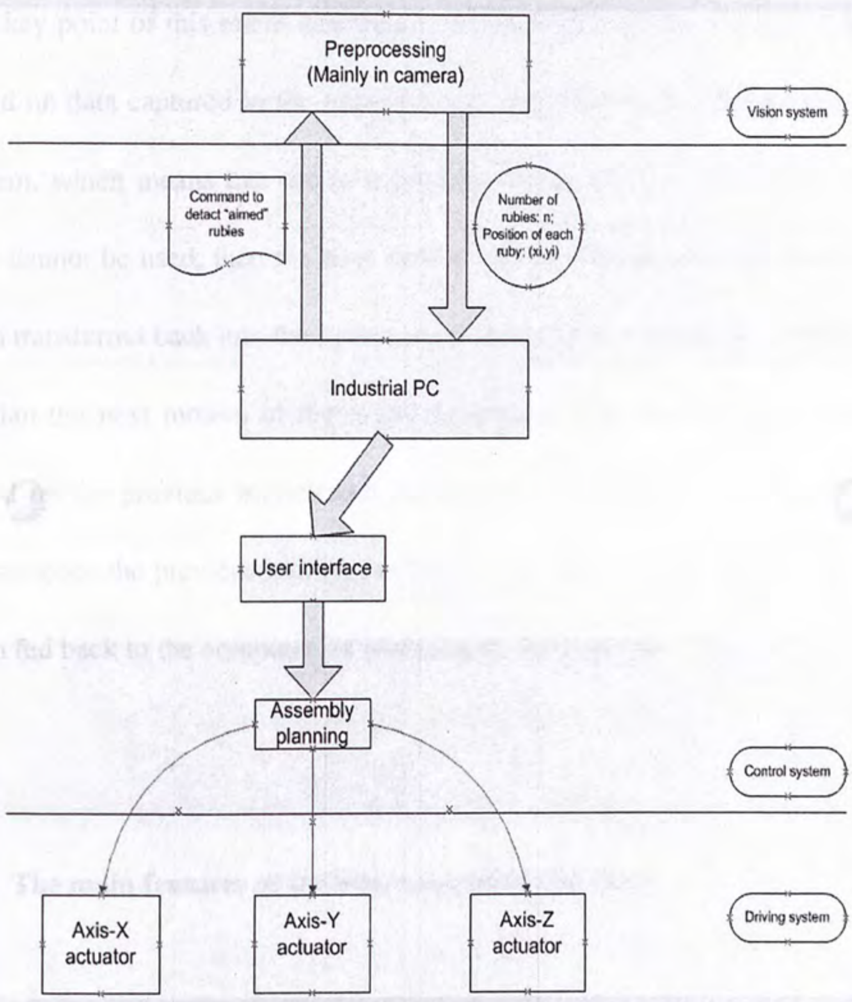


Figure 2-11 Micro assembly machine

The complete structure of the micro assembly machine is shown in Figure 2-12 to give a clear overview of the system. The structure consists of preprocessing work, data transfer to the industrial PC, and assembly commands that are sent to the actuating system and vision system. The vision system, commanded by the industrial computer, captures data on the position of the ruby bearings and main plate bearing holes, which are then transferred to the industrial computer.

The key point of this micro assembly machine is that the next motion step is always based on data captured in the previous step. If no data is transferred from the vision system, which means that the ruby bearings have run out or the main plate-bearing hole cannot be used, then the next motion will not be initiated. However, if data has been transferred back into the system, then the software module will absorb these data to plan the next motion of the actuating system. Basically, the next step motion is based on the previous motion and the feedback data. The next motion step is only known once the previous motion has been completed and the data on this motion has been fed back to the computer for planning the next motion.

2.3. The main features of the micro assembly machine

The main features of the micro assembly machine that distinguish it from other high-accuracy assembly machines can be listed as follows.

1. Low environmental requirements (e.g., no need to enclose the whole system).
2. High precision and accuracy (up to 1.9 μm).
3. High speed (typically, 3.6 m/s and 1 m/s^2).

3. Implementation

The various hardware parts of the micro assembly machine are connected by software modules. The hardware components are individual pieces of equipment that cannot work collaboratively as a whole machine without software modules. This chapter presents the implementation of the system, and details the software modules used in the vision and control systems and the graphic user interface (GUI).

3.1. Vision system

The vision system is used to improve the efficiency and accuracy of the machine. It is very hard for a micro assembly machine to detect ruby bearings and bearing holes, the dimensions of which are usually in millimeters (Table 1-1). However, this problem is easily solved with the use of a vision system (see Figure 3-1). The vision system contains a camera (Model: CV-200C), a monitor, a twenty-four volt power supply (Model: CA-U2), a controller unit (Model: CV-3502), and a set of operation equipment (used to determine the appropriate settings). The vision system can simulate its settings before putting them into practice using a PC that is connected to the system through an Ethernet, USB, or RS-232 connection. The vision system works under the best settings that make it most efficient after several simulations. The vision system is connected to the industrial PC through the computer's RS232 port, and feeds it data on the position of the ruby bearings and bearing holes.

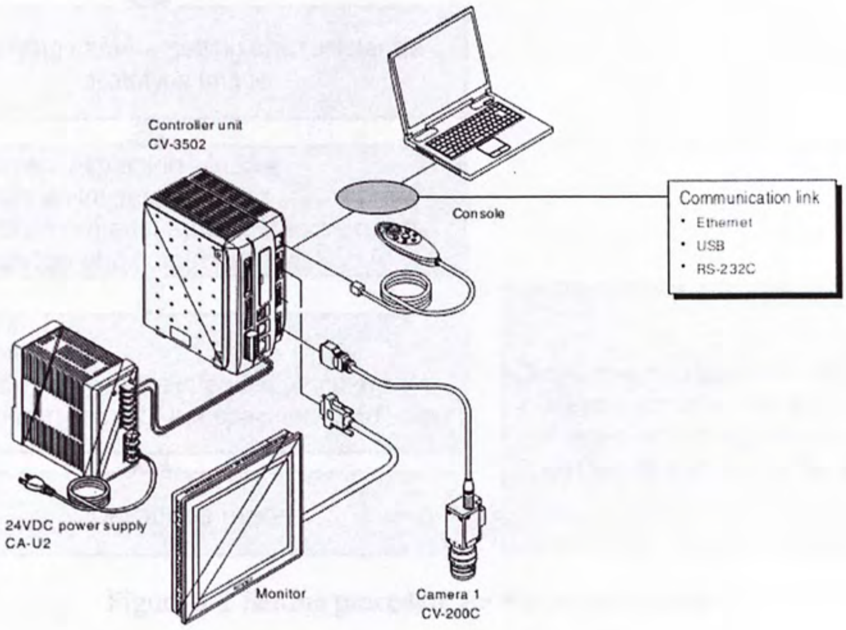


Figure 3-1 Vision system

3.2. Setting up the vision system

Because the vision system supplies positional data on the ruby bearings and bearing holes to the control system, the settings of the system are very important. If the data supplied are not accurate due to the use of unsuitable settings, then the accuracy of the whole system will be affected. It is necessary to follow a stepwise procedure to obtain the right settings for the vision system, as shown in Figure 3-2.

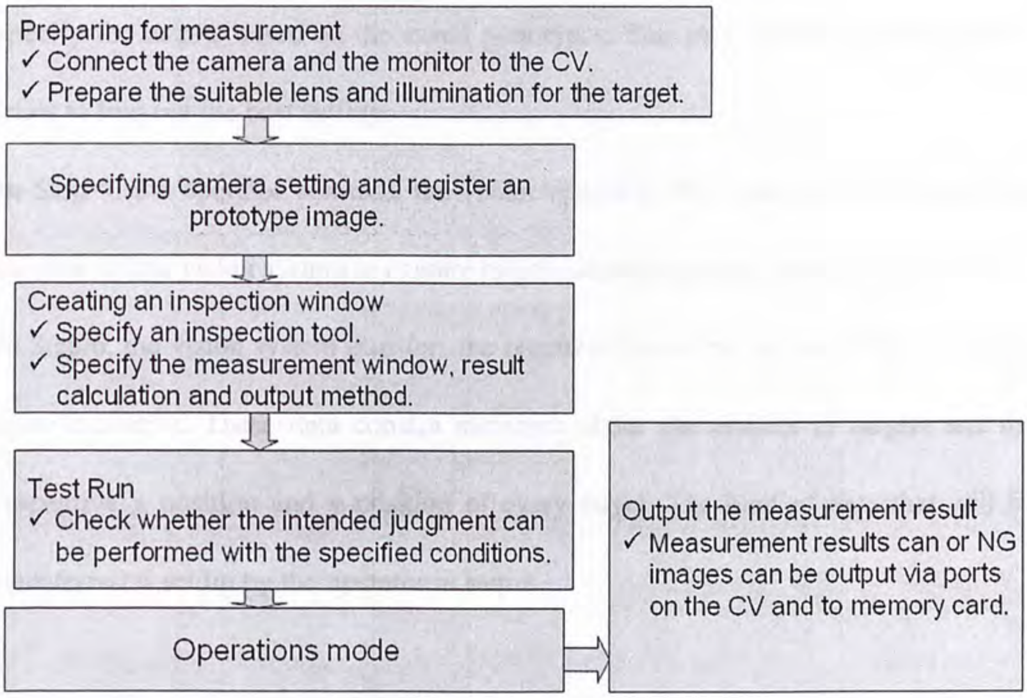


Figure 3-2 Setting procedure for the vision system

In Step 1, the CV-3502 is connected to the camera and monitor. The camera obtains images, and the monitor shows in real time the images captured by the camera. The camera should be appropriately tuned to obtain a clear monitor picture.

In Step 2, the operator specifies the camera settings in CV-3502. The prototype images of five kinds of ruby bearings and their five corresponding plate bearing holes are input into the vision system. These prototype images are then used as benchmarks to distinguish the targets set by the system.

In Step 3, the operator specifies which part of the prototype image contains the target.

This makes the target easy to specify by enhancing the contrast between the target and the environment around it.

In Step 4, the operator runs simulations to determine whether the vision system can specify the targets based on the saved prototypes. This step usually involves several trials to find out the best setting.

In Step 5, the operator connects the vision system to the industrial PC, which then commands the vision system to capture targets according to the respective prototypes.

In Step 6, the vision system transfers the required data to the industrial PC for further motion control. These data contain messages about the number of targets and the respective x position and y position of every target. The kind of data that will be transferred is set up by the operator in step 2.

3.3. Efficiency and form of the transferred data

To maximize the transfer efficiency, the Baud rate of the RS232, which connects the vision system and the industrial PC, is set to 9600 bps. The parameters passed to the computer from the vision system are in the form of "T1,xx,xxx.xxxx,xxx.xxxx." The transfer time can be calculated as 24*4/9600 seconds $\approx$ 0.01 second at a Baud rate of 9600 bps. "T1" is the command that triggers the vision system to transfer the required parameters. The parameters after "T1" refer to the number of targets, the target's x position, and the target's y position, in that order.

As these data are in ASCII form, they must be transformed into numerical form before they can be used by the program. The transformation program is best described using the example of a message transferred from the vision system: "T1,01,012.3456,123.4567." There are twenty-four ASCII characters in this message: the first one is "T," the second one is "1," the third one is ",", the fourth one is "0," the fifth one is "1," and so on. As the position of these data is fixed, the first two characters are always the trigger command, the third one is always a comma, the fourth and fifth are the number of targets, and the seventh to fourteenth are the x position. Thus, in this example, $10\times0+1\times1$ is the number of targets, and the x position of the target is $100\times0+10\times1+1\times2+0.1\times3+0.01\times4+0.001\times5+0.0001\times6 = 12.3456$. The y position is transformed to numerical form in the same way. The ASCII characters "01," "012.3456," and "123.4567" are also transformed into numerical form through this process. The control system, which is detailed in the next section, then commands the micro assembly machine to fetch the target at position (12.3456, 123.4567) after these values have been transferred to the control system.

3.4. Control system

This section explains how the control system uses the data obtained from the vision system and the industrial PC and commands the motion of the machine.

3.4.1. Structure of the control system

The structure of the control system is shown in Figure 3-3. Each part of the control system is modularized, which means that each part can be replaced with other similar equipment with little change in programming being required.

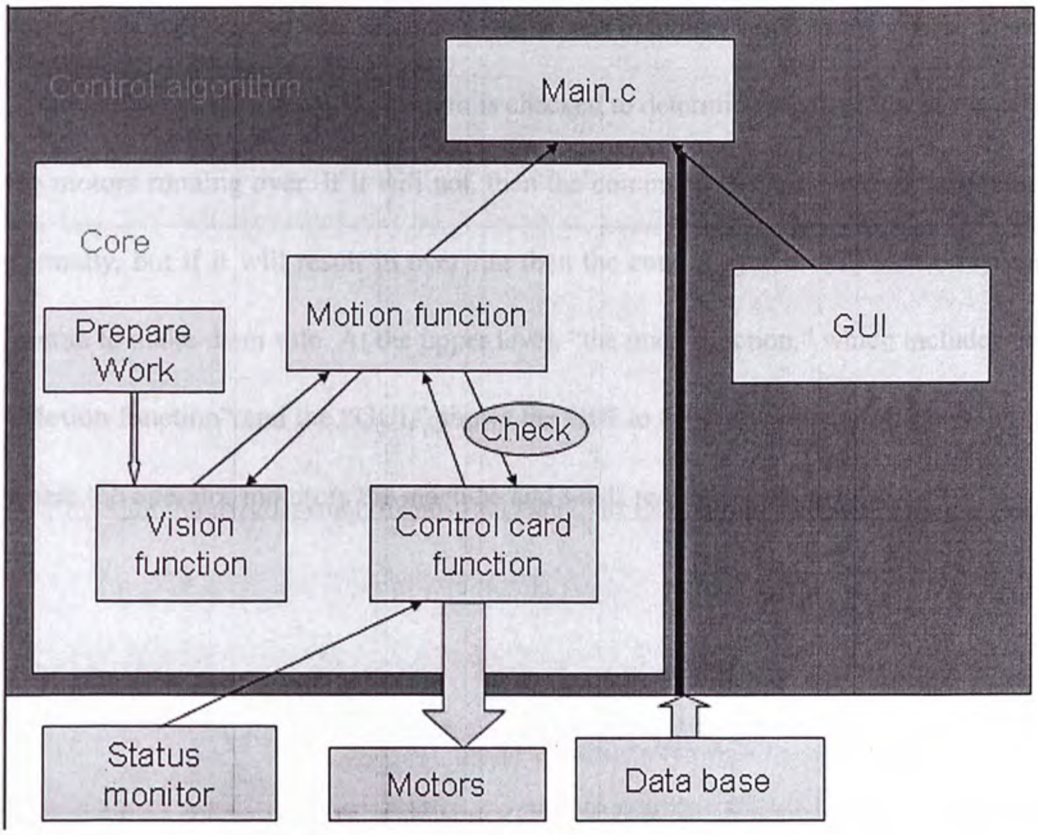


Figure 3-3 Control system and its relationship with the other equipment

The "Control card function" file is the file that "talks" to the controller. It transfers the commands from the "Motion function" to the controllers and also transfers the motor status back to the "Motion function" as positional data. The "Vision function" is a modularized function that "talks" to the vision system. It commands the vision system to work and record the target positions and feeds them back to the "Motion function." The data that is fed back from the "Vision function" and "Control card function" is processed in the "Motion function," which also sends commands to the vision system and motors. There is also a "check" module that verifies whether the motion commands given to the motors will make the motors run out of region before the commands are sent to the motors to make the machine work more safely. Every command sent to the actuating system is checked to determine whether it will result in the motors running over. If it will not, then the command is transferred to the motors normally, but if it will result in over run then the control system will shut down the motors to make them safe. At the upper level, "the main function," which includes the "Motion function" and the "GUI," shows the GUI to the human operator. The GUI is where the operator monitors the machine and sends real-time commands.

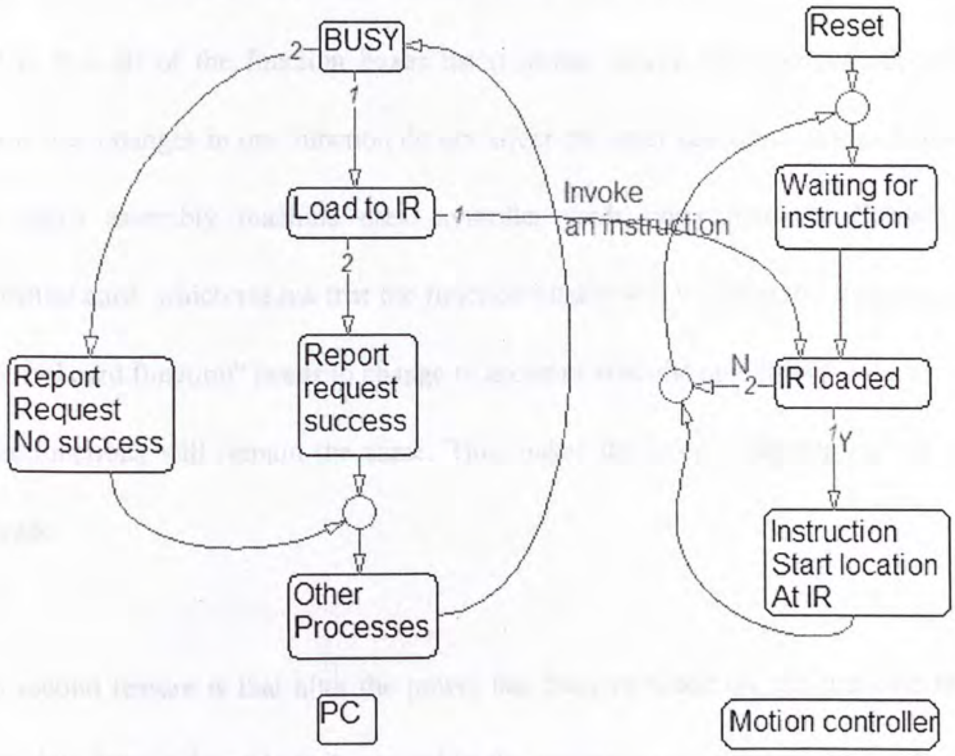


Figure 3-4 Communication between the computer and the motion controller

The communication between the computer and the motion controller is shown in Figure 3-4, which illustrates that the motion controller executes each command from the computer line by line. The motion controller's normal status is "waiting for instruction." The instruction comes from the computer. If the computer response request is interrupted, then the instruction will be sent to the motion controller and the motion controller will carry on executing the instruction. The "instruction start location at IR" status and "no IR loaded" status result in the motion controller returning to normal status.

There are several features of the control system that that must be emphasized. The first is that all of the function boxes listed in the picture are modularized, which means that changes in one function do not affect the other functions. For example, if the micro assembly machine uses controller cards other than the GT-400-SV controller card, which means that the function library will be different, then only the "Control card function" needs to change to accommodate the new library, whereas the other functions will remain the same. This makes the system flexible and easy to upgrade.

The second feature is that after the power has been switched on, the machine reads some data from a data file that is saved in the industrial computer to allow it to load some mechanical data about the system, such as the initial height of the gripper heads, the initial position of the workbench, and so on. Keeping these data and loading them at start-up makes setting the machine up for work after a mechanical change convenient and automatic. Taking the initialization of the gripper heads as an example, as has been mentioned, the depth of the ruby bearing is very important and is controlled by the height and motion of the gripper head. If one of the gripper heads has run out after working for a long time and needs to be replaced by a new one, then the operator simply needs to measure the height difference between the old head and the new head and replace the old data with the new data in the data file. The machine will then change the related parameters in the program automatically, rather than the operator having to change each parameter in the program manually.

The third feature is the log file that logs all the status information, which is very useful when there is something wrong with the system.

The fourth feature is that the program is written as a multiple-thread system to make the machine work fluently. For example, the GUI can send commands to the motion controller card while monitoring the position of the motors.

3.4.2. System control process

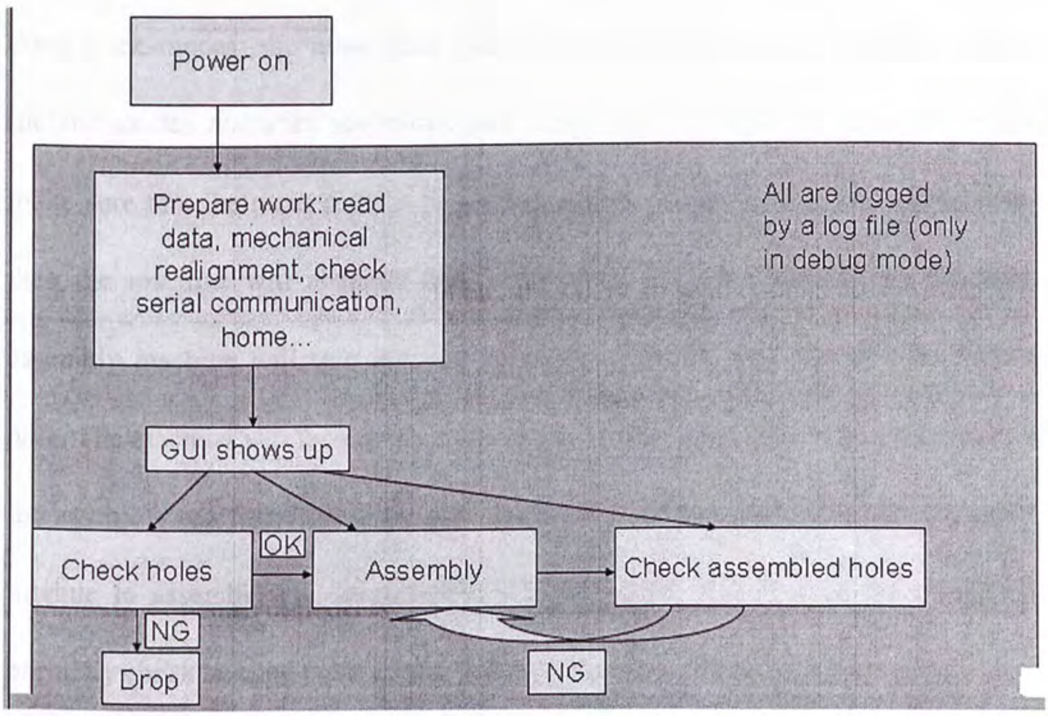


Figure 3-5 Work process

Figure 3-5 shows the flow of the control system process in command flow form. After

"Power on," the system automatically carries out some background preparatory work, such as reading data from a data file, mechanical realignment, serial connection checking, homing, and so on. The monitor shows the GUI once all of these tasks have been completed. The system then goes into real-time control status, and is ready to execute tasks under the user's command as soon as the GUI shows up.

Once the system is in real-time control status, the operator gives the machine a command to start the assembly motion through the GUI and sets some parameters, such as the number of watch main plates to be assembled, the motion velocity, acceleration, and so on. As shown in Figure 3-5, this micro assembly machine has three work modes: the main plate ruby bearing hole check mode, assembly mode (default mode), and after assembly check mode. The "check holes" module is run to make sure that the main plate is in good condition. If the bearing hole is deformed, then the machine will abandon the assembly of it; if it is sound then the micro assembly machine will step into the "assembly" module and assemble the bearing hole. The machine will then check whether the assembly has been successful or not. If the assembly has failed, then the micro assembly machine will rerun the "assembly" module to assemble the corresponding bearing hole. The flow of the machine is normally check bearing holes -> assemble -> check assembled bearing holes.

3.4.3. The GUI

This micro assembly machine has a central computer (industrial computer) that acts as decision-making center. The human operator inputs commands to this computer through the GUI, which is shown in Figure 3-6.

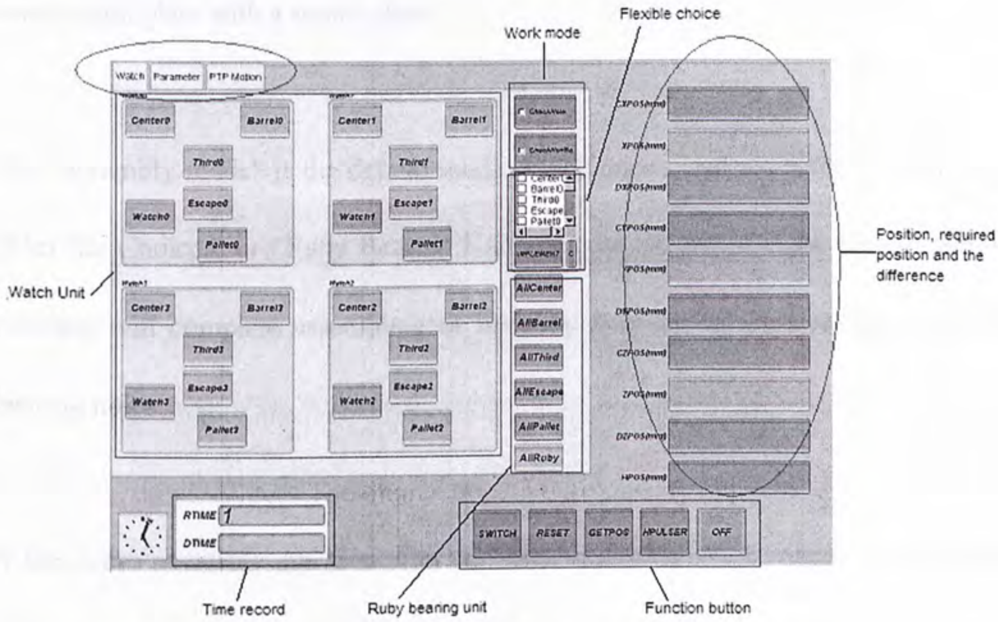


Figure 3-6 GUI

In the GUI, the operator can choose from the "Watch Unit," "Flexible Choice," and "Ruby Bearing Unit" work modes. "Watch Unit" means completing a task at the whole watch level, "Flexible Choice" means that the task will only be performed on the selected main plate bearing holes, and "Ruby Bearing Unit" means that the task will be performed on the same kind of watch main plate bearing hole.

As has been stated, the "check main plate ruby bearing hole" mode is used to check whether the watch main plate is in good condition. Once this mode has been chosen, pressing the "Watch Unit," "Flexible Choice," and "Ruby Bearing Unit" buttons only results in the machine checking the corresponding state of the watch main plate. If the main plate is not in good condition, then the GUI will change the color of the relevant bearing hole button in the "Watch Unit" function to tell the operator to replace the bad watch main plate with a sound plate.

The "assembly mode" is the default mode, which means that when the "Watch Unit," "Flexible Choice," or "Ruby Bearing Unit" buttons are pressed, the micro assembly machine will complete assembling of the ruby bearings in the relevant main plate bearing holes.

If the micro assembly machine is in the "after assembly check mode," then pressing the function buttons will only result in the machine checking whether the assembly has been successful or not. If it has failed, then the GUI will change the color of relevant button in the "Watch Unit" to tell the operator to reassemble.

The GUI also has other functions. For example, the "Position, required position and difference" function shows the real-time position of the workbench, the command position, and the difference between them, and the "Function Button" activates additional functions, such as servo off and handy pulse mode switch.

3.4.4. Data processing

The GUI was written using Fast Light Tool Kit (FLTK) in the Visual C++ 6.0 environment, and serves as the communication bridge between the operator and the micro assembly machine. The data that are fed back from the vision system and the status of the motors are processed by Matlab in the background.

Matlab DLL is used because it simplifies the data process, improves the program efficiency (by 33%), and strengthens the program's privacy. Matlab is good at matrix process and picture functions, whereas c and c++ are good at logic flow and logic efficiency (in contrast to Matlab, which, like BASIC, is "one side explain and one side execute") and GUI development. The combination of the two languages gives the advantages of each, which allows the machine to run at a more efficient level.

There are two ways in which visual c++ can cite Matlab. The first is through the Matlab engine, and the second is through Matlab C functions. As the Matlab engine must be used in a Matlab environment but Matlab C does not have this requirement, the Matlab C function is used to build DLL files in our system.

Although the programming of the system is designed to register the positions of all of the eligible ruby bearings and bearing holes in one window, it is restricted to registering them one at a time. If the system registered several different positions of ruby bearings and bearing holes at the same time, then it will not take into account any positional change that would result after motion (especially for the ruby bearings because they are very light), which could result in assembly failure.

The data recorded during the motion is transfer to a Matlab DLL, which handles the data and presents the motion curve to the operator in a Matlab figure window. The DLL can also work on a computer that does not have Matlab installed, but an MCR must be built in the original Matlab settings and set up in the target computer.

3.5. Cooperation between the vision system and the control system

The XY linear-driving system drives the workbench to the view domain of the camera once the assembly motion has been started. The vision system then transfers the number of identified ruby bearings and their respective coordinates to the industrial computer through the RS232 port. The software module in the industrial computer converts these ASCII data into numbers that can be calculated in c language. The data are then used to plan the next motion. Once the workbench has reached the next target position, the cycle is run again.

The commands from the central computer are further processed at a lower control level by the control card and vision system, and are resolved into a defined command sequence to activate the system components by the industrial computer. The movements between the motors are controlled by the industrial PC.

4. Experimental results

A large number of experiments have been performed to evaluate the performance of the developed micro assembly machine, and results on the positional accuracy of the x-y table and the ruby bearing assembly accuracy (depth and gradient of the assembled ruby bearings) have been obtained.

The ruby bearings function to keep the neighboring pinions meshed. To achieve this target, at least three types of accuracy need to be guaranteed: the position in the x and y directions, the depth of the assembled ruby bearings in the corresponding bearing holes, and the gradient of the assembled ruby bearings. The experimental results regarding these measures of accuracy are detailed in the following sections, and together determine whether the assembly of the watch ruby bearings using the machine is successful. The experimental results were obtained with an x and y motor velocity of 3.6 m/s.

4.1 Accuracy in the x and y directions

A Renishaw XL-80 Laser Calibration System (shown in Figure 4-1) was used to measure the accuracy of the two HIWIN linear motors that drive the watch workbench in the x and y directions. The results are shown in Figure 4-3 and Figure 4-4.

Figure 4-1 Renishaw XL-80 Laser Calibration System

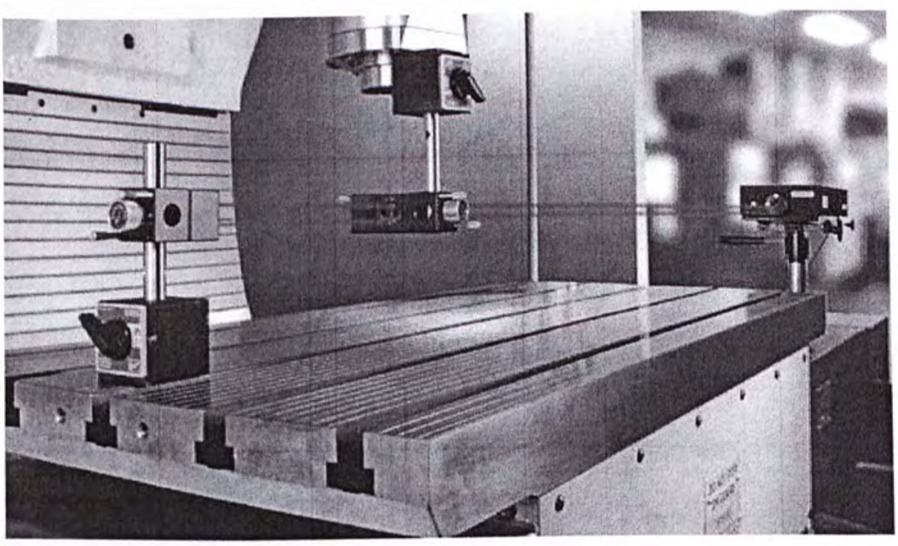


Figure 4-2 Setup of the Renishaw system

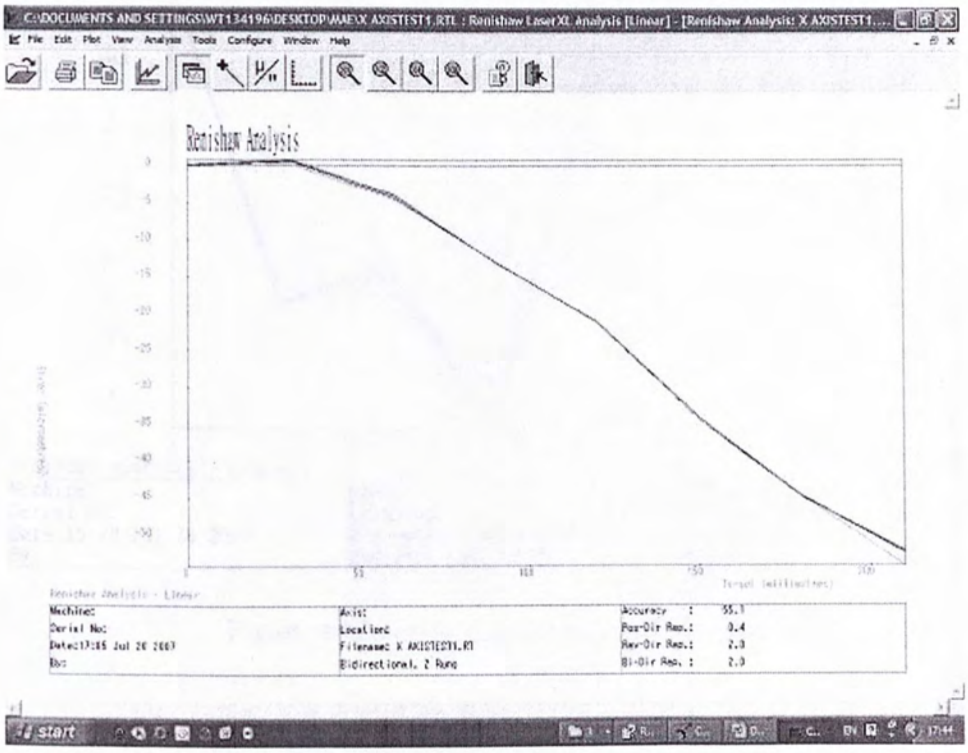


Figure 4-3 Renishaw analysis results for the x axis

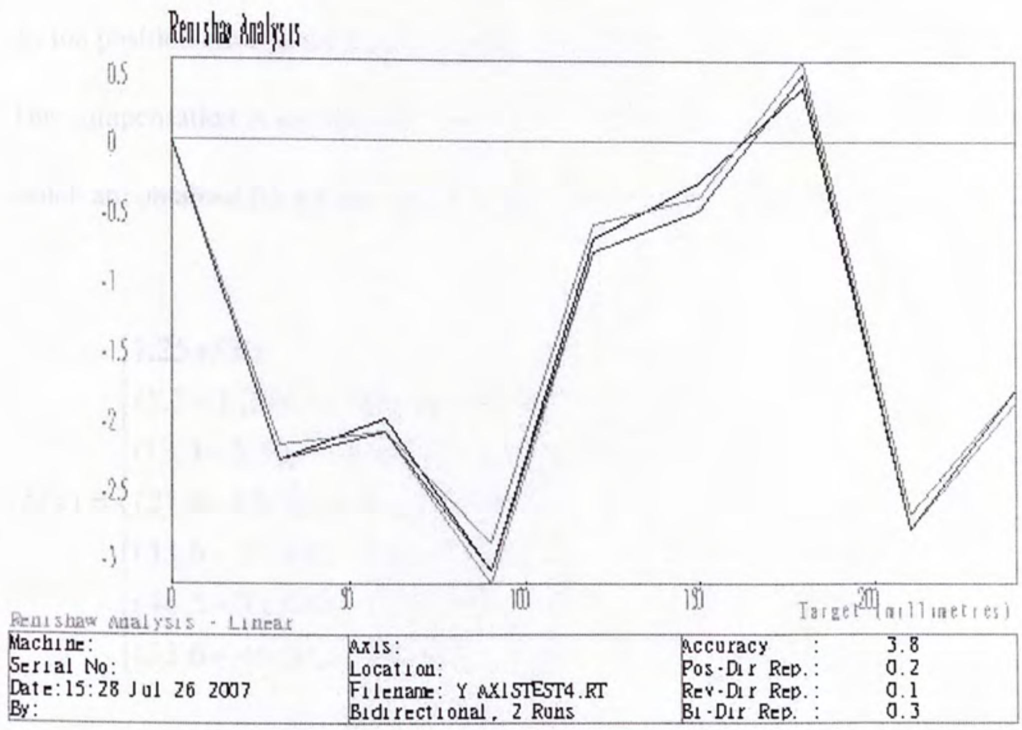


Figure 4-4 Renishaw analysis results for the y axis

Figures 4-3 and 4-4 give the results for the accuracy of the two linear motors with the earth as the frame of reference. The measured accuracy for the x and y axes is presented in Table 4-1.

Axis	X	Y
Pos-Dir Rep	0.4 μm	0.1 μm
Rev-Dir Rep	2.8 μm	0.1 μm
Bi-Dir Rep	2.0 μm	0.3 μm
Accuracy	55.1 μm	3.9 μm

Table 4-1 Renishaw analysis results

As the position error in the y axis is small, compensation is only needed for the x axis. The compensation is carried out based on the following equation, the parameters of which are obtained from Figure 4-3 with the linear interpolation method.

$$f(x)=\begin{cases}1.25x/30 & 0\le x<30mm\\(5.5-1.25)(x-30)/30+1.25 & 30\le x<60mm\\(13.3-5.5)(x-60)/30+5.5 & 60\le x<90mm\\(21.4-13.3)(x-90)/30+13.3 & 90\le x<120mm\\(33.6-21.4)(x-120)/30+21.4 & 120\le x<150mm\\(44.5-33.6)(x-150)/30+33.6 & 150\le x<180mm\\(53.6-44.5)(x-180)/30+44.5 & 180\le x\le 210mm\end{cases}.$$

where, x is the distance in the X-axis from the end. Since the home position of the work bench is set to be 1091491 counts and the resolution for X-axis is 0.1 μm / counts, the home position is 109.1491 mm from the end. So, the above equation becomes:

$$f(x)=\left\{\begin{matrix}1.25(x+109.1491)/30 & -109.1491\le x<-79.1491mm\\(5.5-1.25)(x+109.1491-30)/30+1.25 & -79.1491\le x<-49.1491mm\\(13.3-5.5)(x+109.1491-60)/30+5.5 & -49.1491\le x<-10.1491mm\\(21.4-13.3)(x+109.1491-90)/30+13.3 & -10.1491\le x<10.8509mm\\(33.6-21.4)(x+109.1491-120)/30+21.4 & 10.8509\le x<40.8509mm\\(44.5-33.6)(x+109.1491-150)/30+33.6 & 40.8509\le x<70.8509mm\\(53.6-44.5)(x+109.1491-180)/30+44.5 & 70.8509\le x<100.8509mm\end{matrix}\right\}$$

where, x is for the distance from the home position of the X-axis. The compensation is built into the control software. For example, if the position in the x direction is 35 mm, then the actual position will be compensated by the section of 10.8509 ~ 40.8509 mm in the equation, that is:

$$(33.6 - 21.4)(35 + 109.1491 - 120) / 30 + 21.4 = 31.2206$$

The measured results for the x axis after compensation are shown in Figure 4-5 and Table 4-2.

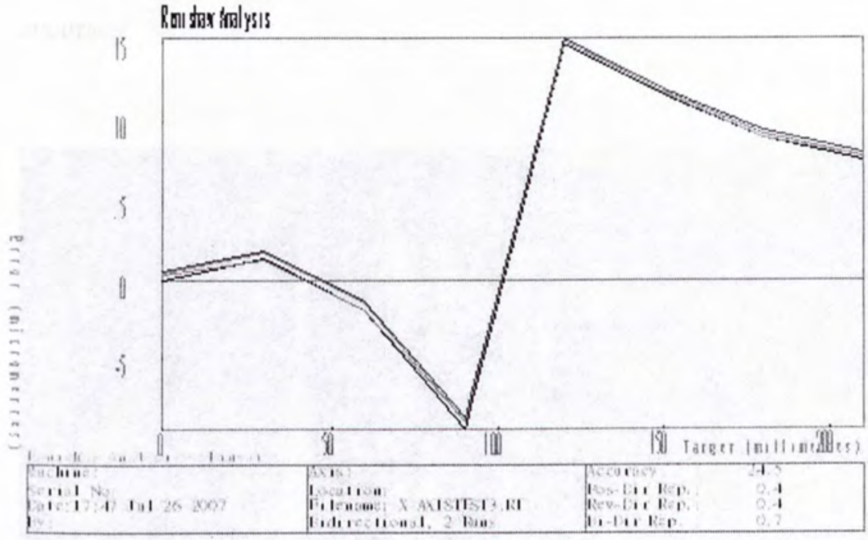


Figure 4-5 Renishaw results after compensation

Axis	X	Y
Pos-Dir Rep	0.4 μm	0.1 μm
Rev-Dir Rep	0.4 μm	0.1 μm
Bi-Dir Rep	0.7 μm	0.3 μm
Accuracy	24.5 μm	3.9 μm

Table 4-2 Renishaw results after compensation

4.2 Effect of the vision system on accuracy

Although the machine would achieve a very high degree of accuracy after compensation (24.5 μm in the x direction and 3.9 μm in the y direction) without the vision system, the inclusion of the system produces an even greater degree of accuracy.

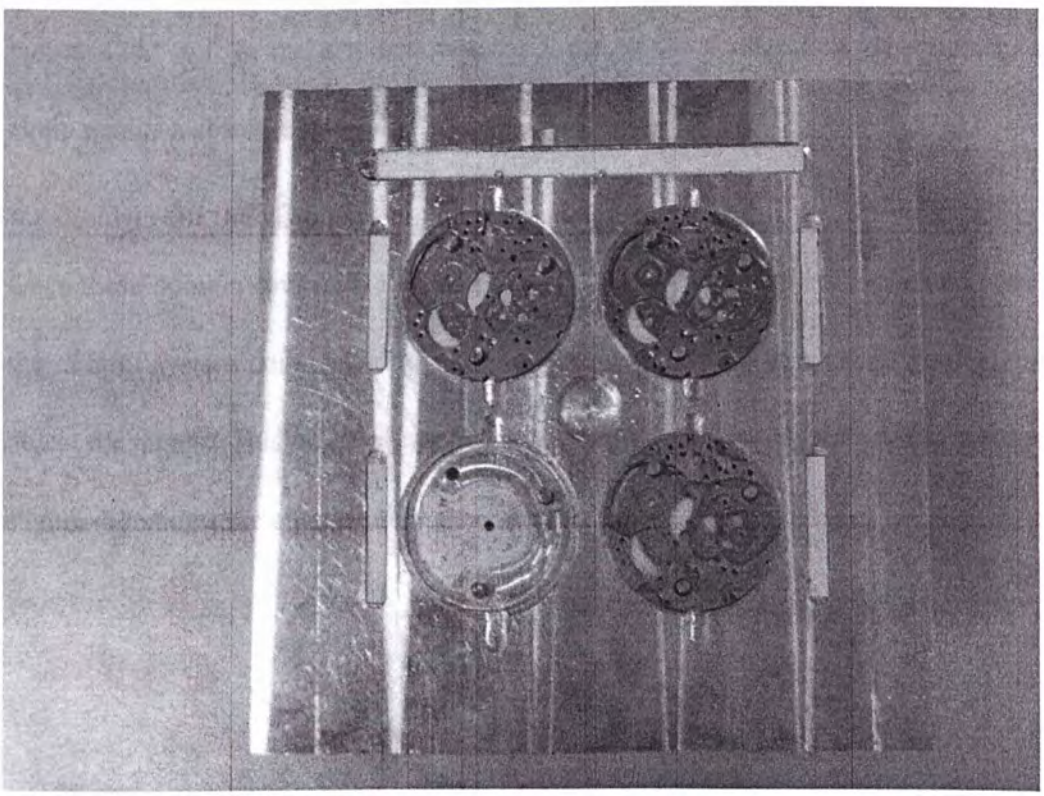


Figure 4-6 Workbench

There are several reasons for this. First, it is necessary to know what kind of data is needed. Figure 4-6 shows the machine's workbench. There are several parameters of the workbench that need to be gathered and transferred by the vision system to the computer program, namely, the vision domain of each ruby bearing hole and each ruby bearing. Domain refers to the position at which the targets are seen in the vision system monitor.

The domain data are obtained from the electrical geared axes encoders of the handy pulse, or the encoders of the linear motors. However, the Renishaw measure results indicate that these data are not the real data because of the original error in the linear motors (24.5 μm in the x direction and 3.9 μm in the y direction). The Renishaw equipment is a absolute reference for the system.

Once these domain data from the handy pulse have been transferred to the computer, the control system commands the linear motors to go to the referenced domains to detect the targets. This process counteracts the original error using the reverse method. Figure 4-7 shows the algorithm for this process.

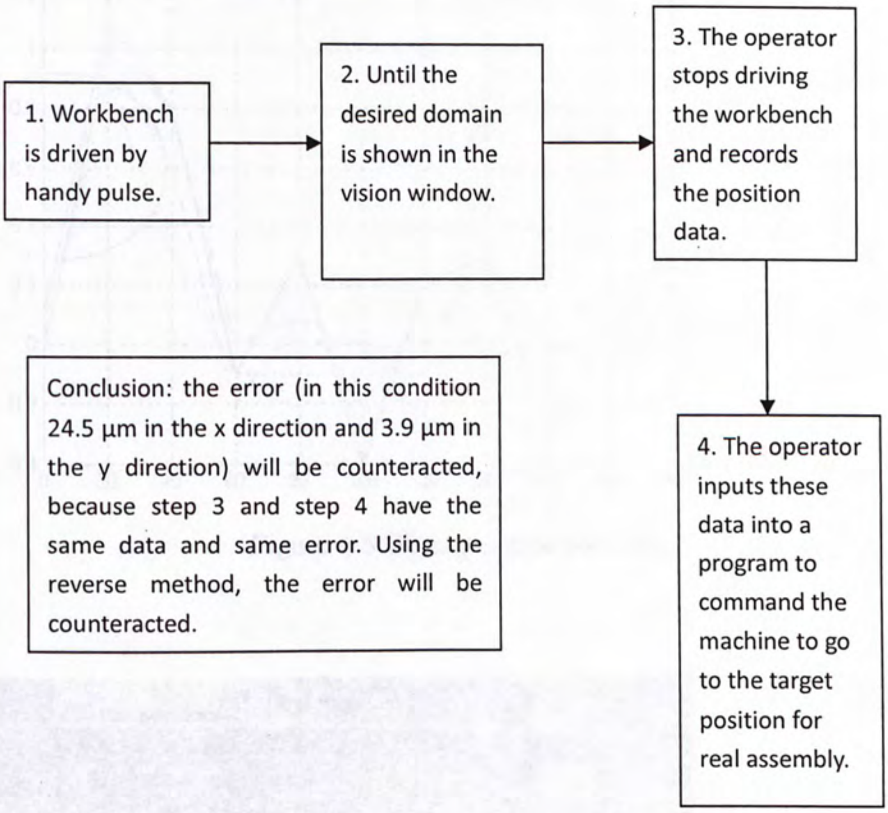


Figure 4-7 Error correction algorithm

The only remaining error is produced by the position of the targets in the single vision window of the vision system. The following paragraphs explain how it can be determined whether this error is the final error of the machine.

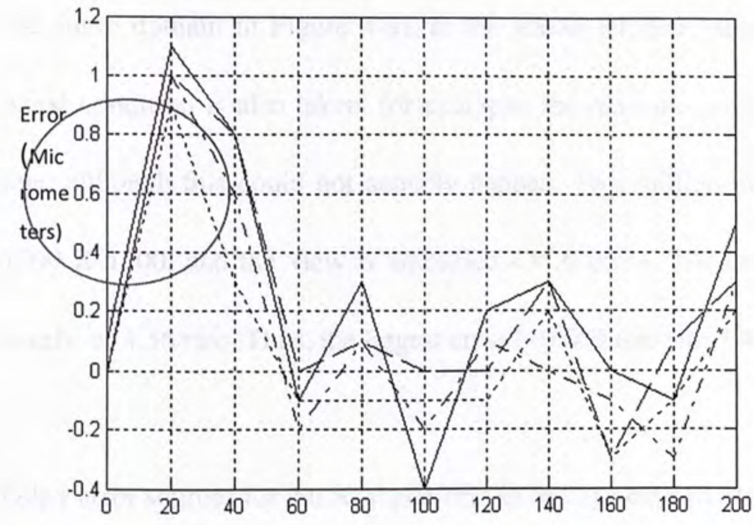


Figure 4-8 Worst position accuracy

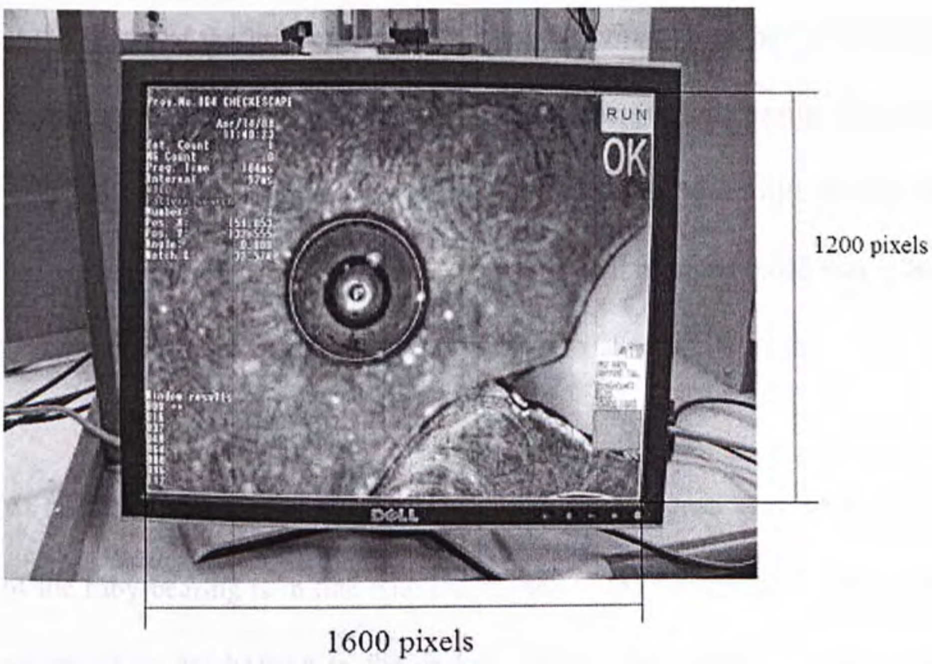


Figure 4-9 Vision window

The worst position accuracy condition between the x and y axes is taken from the Renishaw results curve to make the estimation: 1.1 μm /20mm = 0.055 μm/mm (the red curve domain in Figure 4-8). In the vision window (shown in Figure 4-8), the worst condition is also taken, for example, the machine going over the cater corner line, although this could not actually happen. Two million pixels is almost equal to 1600 X 1200, and the view is amplified 438.6 times. The cater corner line is 2,000 pixels, or 4.56 mm. Thus, the largest error is 0.055 μm/mm * 4.56 mm = 0.2508 μm.

Other error sources for the X-Y platform in this system include the table position error and the ruby bearing position error. The former can be compensated using the method presented in Page 59. The latter occurs as the position of the ruby bearing may not be at the center of the gripper. However, since the gripper head has a little pillar whose diameter is 0.05 mm smaller than the inner diameter of ruby bearings and the oil will push the ruby bearing moving towards the center, this error will be less than 0.025 mm. In conclusion, it is expected the total error will be about 0.025 mm in both X and Y directions.

As for the Z axis, the demand for high accuracy is stringent. This is because the height of the ruby bearing is in line with the surface of the mainplate. In other words, upon placing the ruby bearing to the designed height, the surface of the mainplate will generate a large force stopping the motion of the gripper. Currently, the control of the Z axis is open-loop control without force feedback. As mentioned in Section ?, the maximum force is about 17.5 N. The experiment results indicate that the assembly quality is satisfactory.

4.3 Depth of the assembled ruby bearings

As the ruby bearings are used to hold the watch pillars, which hold the pinions, and the pinions transfer the mechanical movements of a watch, the pinions must be well meshed or the watch will not work properly or may even not work at all.

To achieve full meshing, some of the mechanical structures of the workbench have been improved, such as the inclusion of a supporter under every main plate and covers to hold every main plate.

Experimental data on bearing depth are shown in Table 4-3, where the depth data stand for the distance between a ruby's center and the upper surface of the main plate surface.

	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th
Third	0.001	-0.002	-0.009	0.000	-0.001	0.001	0.008	-0.024	-0.022	0.001	0.006
Escape	0.008	0.006	-0.006	0.005	0.003	-0.012	0.006	0.001	0.003	0.002	0.009
Pallet	0.012	0.021	-0.009	-0.012	0.007	0.008	——	0.005	-0.008	0.014	0.004
Barrel	0.007	0.005	-0.002	0.003	0.006	0.008	0.004	-0.003	0.011	-0.005	-0.004
Center	-0.023	-0.025	-0.022	-0.019	0.011	0.013	0.006	-0.008	0.026	0.029	-0.013

	12th	13th	14th	15th	16th	17th	18th	19th	20th	21st
Third	-0.003	-0.002	0.001	-0.009	-0.001	-0.001	0.001	0.008	-0.024	-0.022
Escape	0.003	0.005	0.006	-0.006	0.005	0.003	-0.012	0.006	0.001	0.003
Pallet	-0.016	-0.012	-0.028	0.003	-0.019	-0.003	0.011	0.012	-0.017	0.026
Barrel	0.004	-0.003	0.002	0.013	0.009	0.007	-0.004	-0.008	-0.002	0.005
Center	0.019	0.012	0.023	0.014	0.017	-0.021	0.018	0.021	0.019	-0.027

Table 4-3 Depth of assembled ruby bearings (mm)

Following figures are the depth data of every ruby bearing.

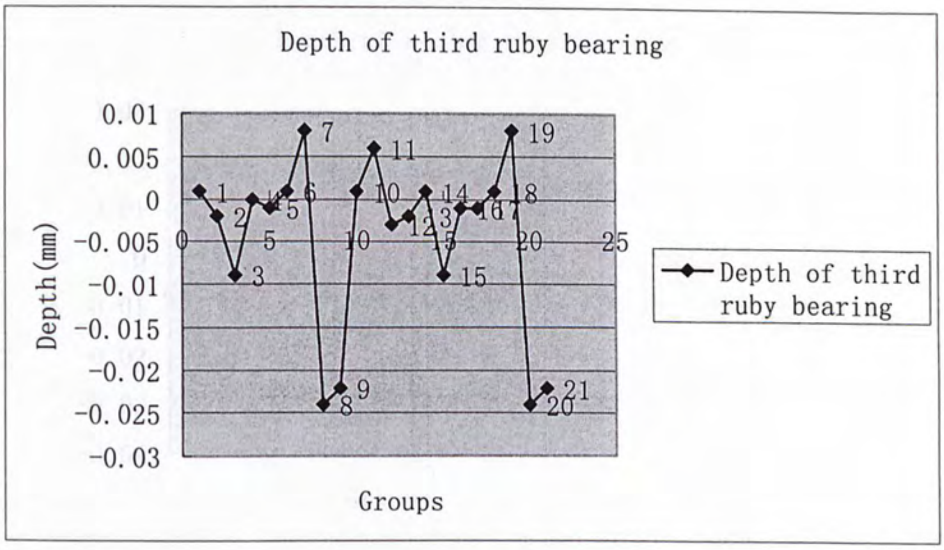


Figure 4-10 Depth of third ruby bearing

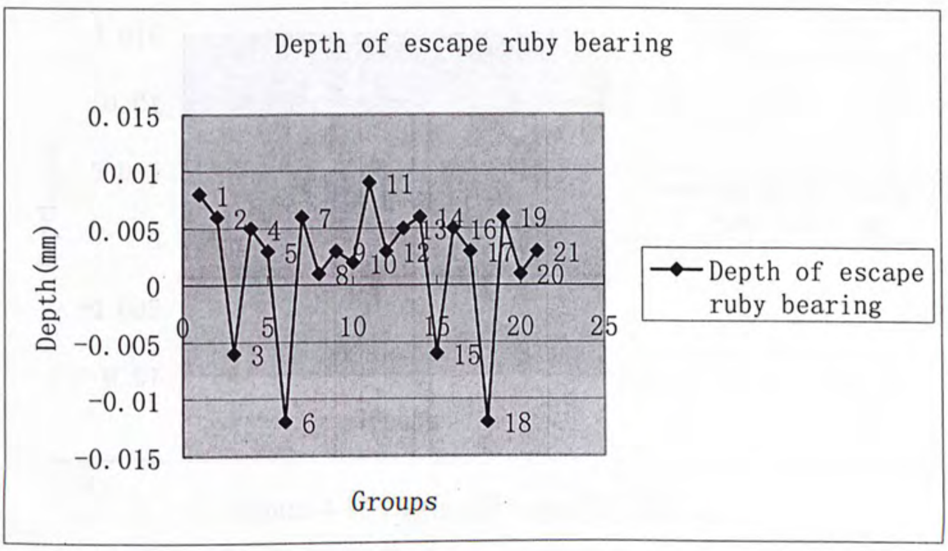


Figure 4-11 Depth of escape ruby bearing

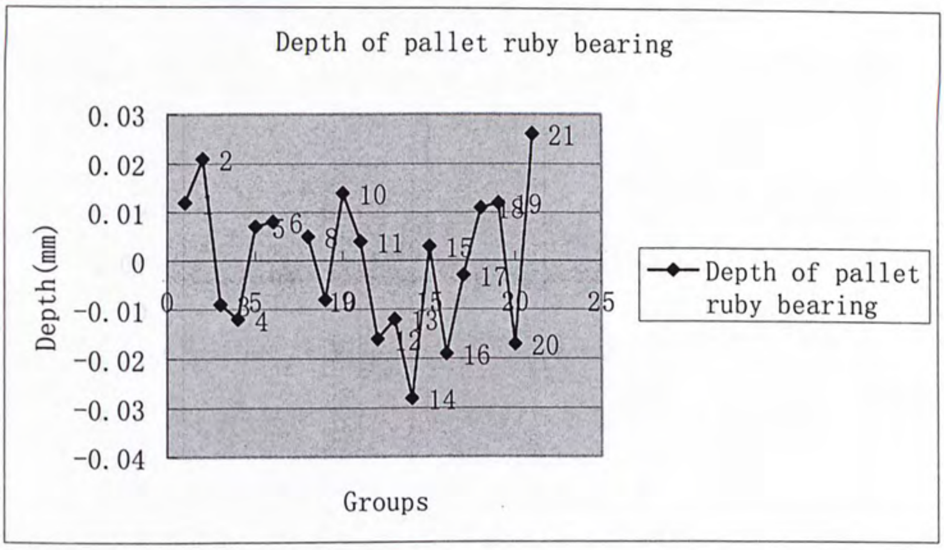


Figure 4-12 Depth of pallet ruby bearing

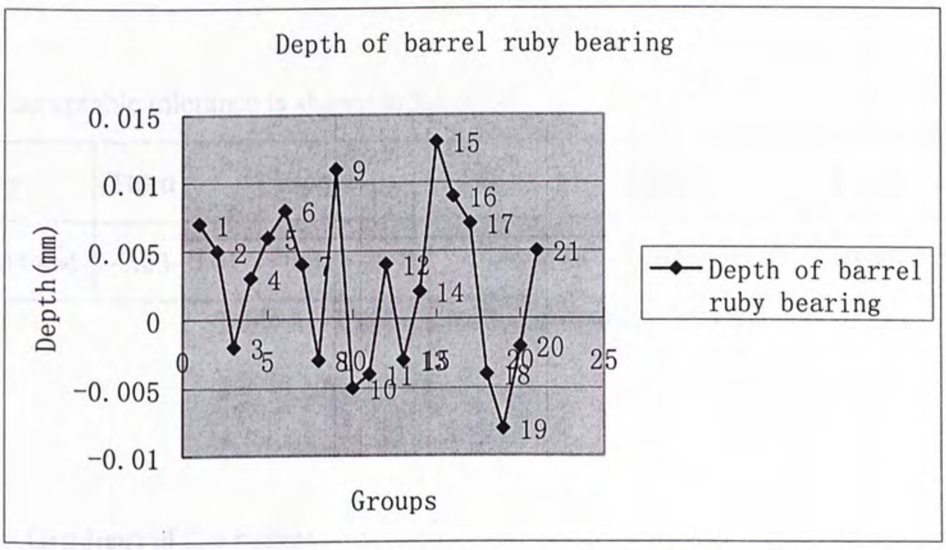


Figure 4-13 Depth of barrel ruby bearing

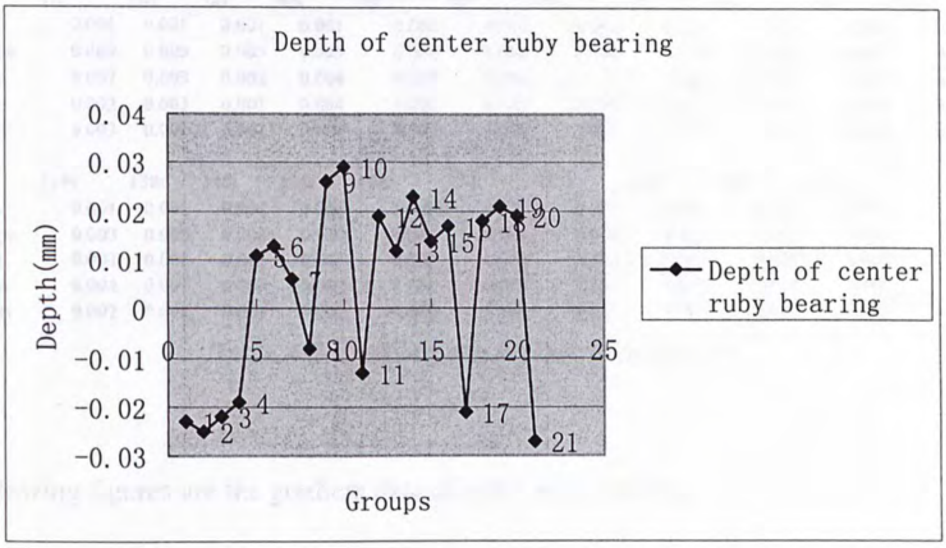


Figure 4-14 Depth of center ruby bearing

The acceptable tolerance is shown in Table 4-4

Ruby	Third	Escape	Pallet	Barrel	Center
Depth bound	-0.03~0.01	-0.015~0.015	-0.04~0.03	-0.01~0.015	-0.03~0.04

Table 4-4 Depth domain requirements (mm)

4.4 Gradient of the rubies

As the ruby bearings are used to hold pillars, they must be set at the correct gradient. If the ruby bearings do not lie flat, then the pinions assembled on the pillars will not mesh with each other. The gradient results are shown in Table 4-5.

	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th
Third	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001
Escape	0.009	0.006	0.003	0.005	0.003	0.008	0.006	0.001	0.003	0.002	0.009
Pallet	0.007	0.003	0.002	0.004	0.003	0.001	——	0.006	0.002	0.003	0.005
Barrel	0.002	0.003	0.001	0.004	0.002	0.002	0.003	0.004	0.006	0.003	0.002
Center	0.003	0.001	0.002	0.004	0.003	0.005	0.001	0.001	0.002	0.004	0.003
	12th	13th	14th	15th	16th	17th	18th	19th	20th	21st	
Third	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.002	
Escape	0.003	0.005	0.006	0.006	0.005	0.003	0.008	0.006	0.001	0.003	
Pallet	0.003	0.001	0.002	0.003	0.007	0.006	0.004	0.003	0.002	0.004	
Barrel	0.004	0.003	0.003	0.002	0.001	0.002	0.004	0.003	0.003	0.001	
Center	0.002	0.001	0.003	0.002	0.002	0.001	0.005	0.003	0.003	0.004	

Table 4-5 Gradient of ruby bearings (radian)

Following figures are the gradient data of every ruby bearing.

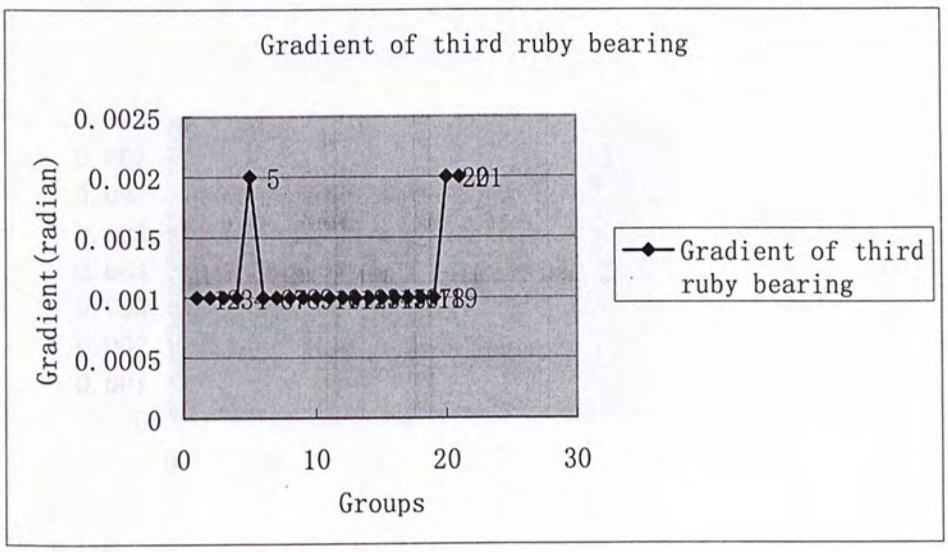


Figure 4-15 Gradient of third ruby bearing

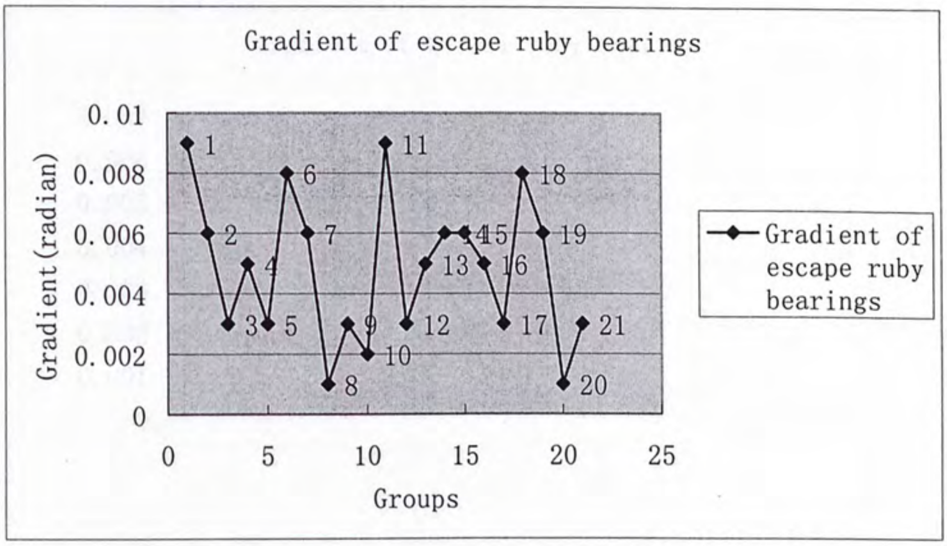


Figure 4-16 Gradient of escape ruby bearing

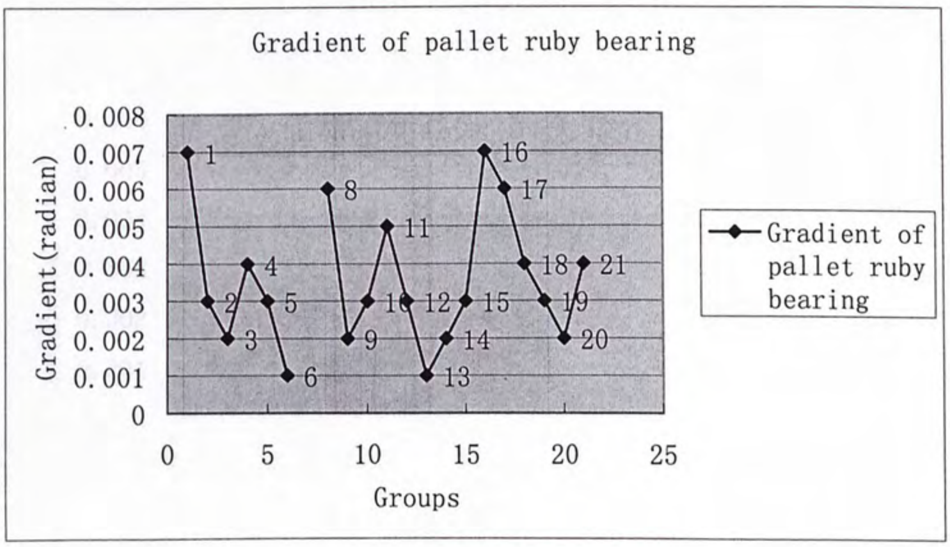


Figure 4-17 Gradient of pallet ruby bearing

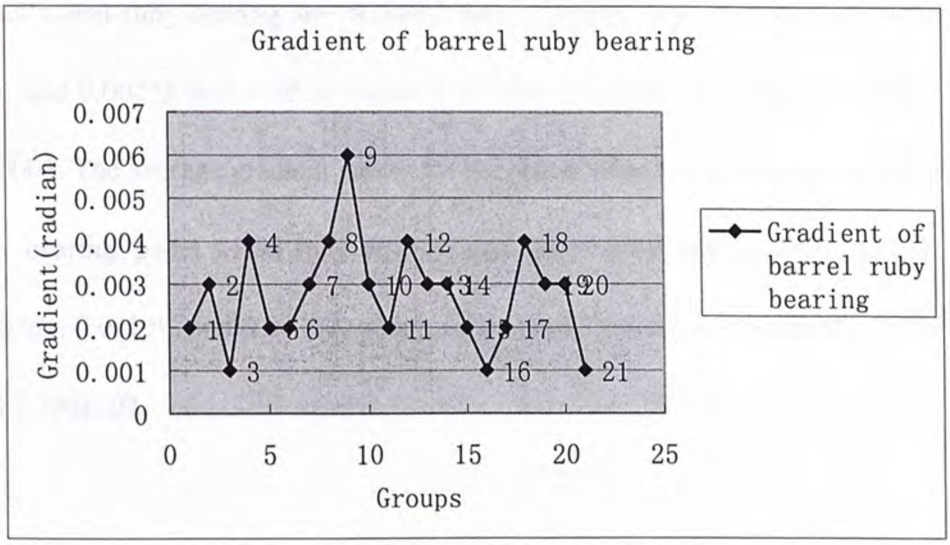


Figure 4-18 Gradient of barrel ruby bearing

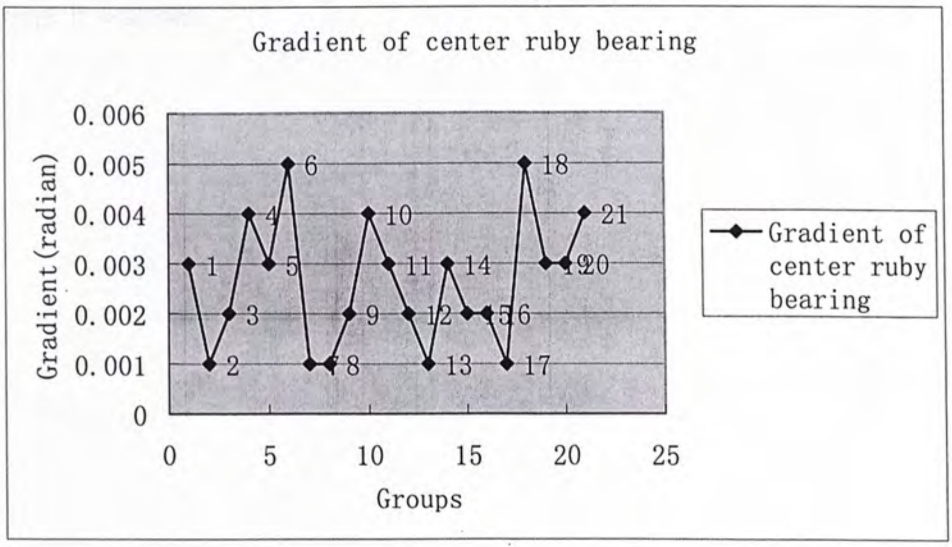


Figure 4-19 Gradient of center ruby bearing

4.5 Analysis of the experimental data

Based on the experimental data, the average depths of the center wheel ruby bearing, third wheel ruby bearing, escape wheel ruby bearing, pallet wheel ruby bearing, and barrel wheel ruby bearing are -0.00842 mm, -0.00828 mm, -0.00931 mm, -0.00272 mm, and 0.00275 mm, with a variance of 0.00423, 0.00013, 0.00005, 0.00005, and 0.00003. The average gradient values for the center wheel ruby bearing, escape wheel ruby bearing, pallet wheel ruby bearing, and barrel wheel ruby bearing are 0.01728, 0.00461, 0.01179, and 0.00202, with a variance of 7.897E-05, 2.440E-05, 3.903E-05, and 7.396E-07.

These experimental data show that the machine can successfully assemble ruby bearings in watches.

5 Conclusion and Future Work

This thesis presents the development of a micro assembly machine for the assembly of the components of a mechanical watch. The micro assembly machine consists of several subsystems, including a gripper that uses using adhesive force to pick up the ruby bearings, a flexible force regulator, and a high-precision and high-speed XY table.

The gripper works through liquid adhesive force, a newly developed micro assembly force that has the advantages of being suitable for many applications and having a low environmental requirement and a low cost. This workbench and gripper of the micro assembly machine both have a flexible structure, and the gripper heads can be changed to assemble miniature parts of different sizes.

The performance of the micro assembly machine has been measured, and the position accuracy of the micro assembly workstation is found to be ± 1.9 μm. The time required to assemble five ruby bearings on one main plate is one minute, which is about twenty times faster than manual operation.

Based on experimental data, the average depths of the center wheel ruby bearing, third wheel ruby bearing, escape wheel ruby bearing, pallet wheel ruby bearing, and barrel wheel ruby bearing compared with the average acceptable tolerance are -0.00842 mm, -0.00828 mm, -0.00931 mm, -0.00272 mm, and 0.00275 mm, with a variance of 0.00423, 0.00013, 0.00005, 0.00005, and 0.00003. The average gradient values for the center wheel ruby bearing, escape wheel ruby bearing, pallet wheel ruby bearing, and barrel wheel ruby bearing are 0.01728, 0.00461, 0.01179, and 0.00202, with a variance of 7.897E-05, 2.440E-05, 3.903E-05, and 7.396E-07. These data show that the machine can successfully assemble ruby bearings in watches.

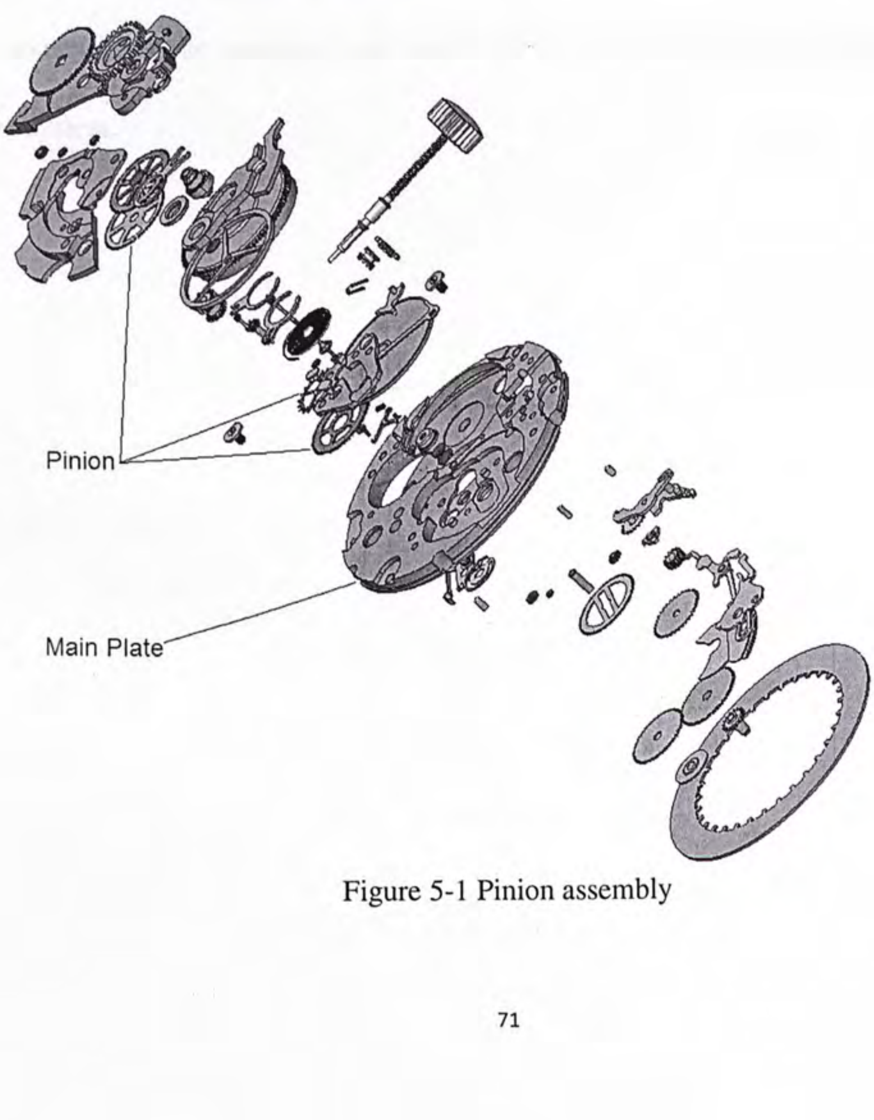


Figure 5-1 Pinion assembly

The machine has successfully assembled the five ruby bearings onto the mainplates of mechanical movements at the speed of 3.6 m/s. The success rate is 99%. It is believed that the high success rate is attributed to several techniques, including the high accuracy of the linear motor drive the X-Y table; the use of the liquid (oil) adhesive force; and the vision based position feedback control system.

At the time of writing this thesis, a new and product-quality application of the micro assembly machine was being designed in which the machine is commanded to assemble the pinions of a watch onto the main plate. Figure 5-1 shows the pinions and the main plate. To achieve this new application, a new kind of gripper head and workbench will be developed and some changes will be made to the programming of the system.

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