上海交通大學

SHANGHAI JIAO TONG UNIVERSITY

学士学位论文

BACHELOR'S THESIS

论文题目：NON-CONTACT THICKNESS MEASURING DEVICE FOR COATING PROCESS IN BATTERY MANUFACTURING

学生姓名：陈智扬，李泽方，凌越农，吴佳金

学生学号：517370910165，517021911115，517370910112，517370910229

专　　业：电子与计算机工程，机械工程，机械工程，机械工程

指导教师：吴继刚

学院(系)：密西根学院

上海交通大学

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日期：2021年8月4日　　　　日期：2021年8月4日

电池极片制造涂布工艺中的非接触式厚度测量设备

摘要

本项目为电池极片制造中的涂布生产线搭建了一套非接触式实时厚度测量系统。其花费低于十万人民币，体积小于 1.5 米×1 米×2 米,并能达到正负 0.5 微米的精度。本项目主要的创新点来源于当下最先进涂布工艺测厚方案的诸多限制，包括（1）缺少在涂布生产线上多出位置测厚的灵活性，（2）由进口导致的巨大花费，和（3）笨重的尺寸。本项目中，最关键的工程规格为花费、精度、尺寸和稳定性。最终的设计为一个解决了当前问题的机电一体化系统。其硬件系统为一个包含可移动机构的、被工字梁加强的 C 型架和两个光谱共焦位移传感器，其软件系统包含一个可以获取、滤波并可视化数据的用户图形界面。本项目的主要成果为一个非接触式实时厚度测量系统的原型机，它能满足各项工程规格，并被一系列实验所验证。本原型机在达到用户需求方面表现优异，但在未来电池工厂的应用中仍需要一些修改。

关键词：非接触式测厚，电池极片，涂布工艺，C 形架，光谱共焦位移传感器，图形界面

NON-CONTACT THICKNESS MEASURING DEVICE FOR COATING PROCESS IN BATTERY MANUFACTURING

ABSTRACT

This project builds a non-contact, real-time continuous thickness measuring device for the coating process in battery electrode manufacturing with a cost of less than 100,000 RMB, a size smaller than 1.5 m × 1 m × 2 m, and resolution of ± 0.5 μm. The primary motivations of this project are the current state-of-the-art solutions' (1) lack of flexibility to measure the thickness of the coating at different locations along the coating line, (2) huge cost to be imported from overseas, and (3) cumbersome large size. The key specifications of this project are cost, resolution, size, and stability. The final design is a mechatronic system that solves the current problem. The hardware part is majorly composed of an I-beam reinforced C-shaped frame with movable mechanisms and two confocal displacement sensors, and the software part contains a graphical user interface for acquiring, filtering, and visualizing data of this project. The outcome of this project is a prototype of a thickness measuring system that meets the specifications, which has been validated under a series of experiments. The prototype is suitable for meeting the customer requirements but still needs some minor modifications for future usage in battery factories.

Key words: Non-contact thickness measuring system, Battery electrode, Coating Process, C-shaped frame, Confocal displacement sensor, Graphical User Interface

Contents

Chapter 1. Introduction

The coating process is to add one or multiple layers of coating material to a substrate. This process has been widely used in textile ([1], SHIM, 2019: P.11-45), corrosion protection ([2], AKSU, 2019: P.453-476), battery, and other industries. Roll coating is the kind of coating that is pre-metered. It uses meters and applies coating liquid on a substrate with a series of rollers ([1], SHIM, 2019: P.11-45). Roll coating is the primary technology for battery electrode manufacturing, which is shown below in ILLUSTRATION 1.1.

ILLUSTRATION 1.1 Coating Process in Battery Manufacturing in CATL Factory ([3], 中国化学与物理电源行业协会, 2020)

Contemporary Intelligent Manufacturing Co., LTD (CIML) was co-founded by Contemporary Amperex Technology Co., LTD (CATL) and Advanced Intelligent Manufacturing Systems (AIMS) in 2020 and is currently working on informatization and process control of battery manufacturing in CATL factories.

Previously, in CATL factories, the solution is to embed the measuring device of battery electrode thickness to the production line. This machine is imported from overseas and is costly. Since the measuring device and the production line are both settled, it can only monitor the coating thickness after the coating layer has been dried through an oven of a length of tens of meters. Large in size, it is not flexible enough to measure the coating thickness on other locations of the coating line. A novel measuring device for the coating process in battery manufacturing with flexibility and low cost is in need.

This project aims to design and manufacture a thickness measuring device for coating process monitoring in battery electrode manufacturing with low cost, small and flexible size, and high precision in response to the previous issues, as is required by the sponsor from CIML. A more detailed description of our design specifications is listed as follows:

a. Cost: less than 100,000 RMB
b. Size: smaller than 1.5 m × 1 m × 2 m
c. Target Resolution: ± 0.5 μm
d. Stability: pass measurement system assessment (MSA)

The outcome of this project is a real-time, continuous thickness measuring device with the properties described above.

Chapter 2. Design Specification

2.1 Literature Review & Benchmarking

2.1.1 Literature Review on Measurement Methods

There are quite a few coating thickness measurement methods in practice, including but not limited to the magnetic method, eddy current method, ultrasonic method, confocal displacement method, micrometer method, cross-sectioning method, and gravimetric method ([4], BEAMISH, 2000: P.559-564). For the case CIML is facing, only the first four non-destructive measurement methods are eligible for consideration. The summary of these four methods is as follows.

a. Magnetic Method

The magnetic method works to measure nonmagnetic coating layer thickness on magnetic substrates. As the thickness of the nonmagnetic coating changes, the measured magnetic flux density induced by magnet changes, as shown in ILLUSTRATION 2.1. Therefore, the coating thickness can be determined. The magnetic method is a proven technology, and related standards include ASTM standards B 499, B 530, and D 1186, although the measuring process is complex and relatively low in the precision of 3% ([4], BEAMISH, 2000: P.559-564)

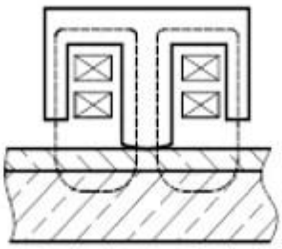


ILLUSTRATION 2.1 Induced Magnetic Field, reproduced from ([5], 彭雪莲, 2004: P.80-82)

b. Eddy Current Method

The eddy current method works through electromagnetic induction of the substrate material. A coil with a high-frequency alternating current inside can induce an eddy current in the substrate (ILLUSTRATION 2.2), related to the coating thickness. Another coil can sense this eddy current, and thus the thickness of the coating is determined. Relative standards include ASTM standards B 244 and D 1400.

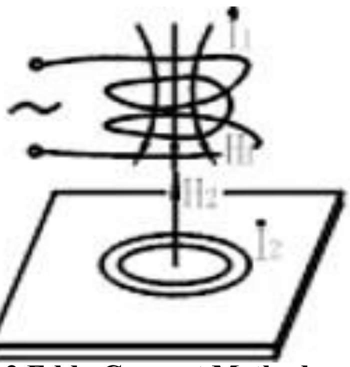


ILLUSTRATION 2.2 Eddy Current Method, reproduced from ([5], 彭雪莲, 2004: P.80-82)

c. Ultrasonic Method

The ultrasonic method involves local oscillation of the substrate and the coating material combined. The amplitude of local oscillation is inversely proportional to the surface density at the measuring point ([5], 彭雪莲, 2004: P.80-82). Therefore, we can determine the amplitude of oscillation by the transmitter and the receiver indicated in ILLUSTRATION 2.3. Existing sophisticated solutions using this method include MeSys USMX 200.

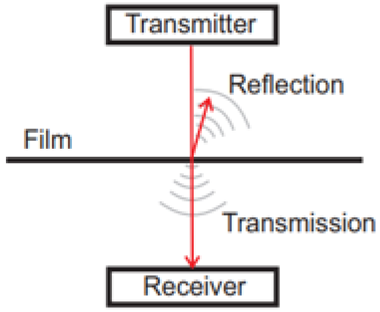


ILLUSTRATION 2.3 Ultrasonic Method ([5], 彭雪莲, 2004: P.80-82)

Confocal Displacement Method

The confocal displacement method is a more advanced method of measuring coating thickness. A lens of a sensor focuses confocal lights of different wave lengths on a single line perpendicular to the surface of the coating, but only the part of the light that focuses on the surface of the coating can be reflected and be detected (which is the green light for the left picture, and the blue light for the right picture in ILLUSTRATION 2.4). Different detected light wavelengths in different distances from the lens to the coating surface. By placing two identical sensors such that their lines of confocal coincide, the thickness of the coating and substrate combined can be measured accurately. Existing sophisticated solutions include the Keyence CL-3000 series and Shenzhen LightE Technology.

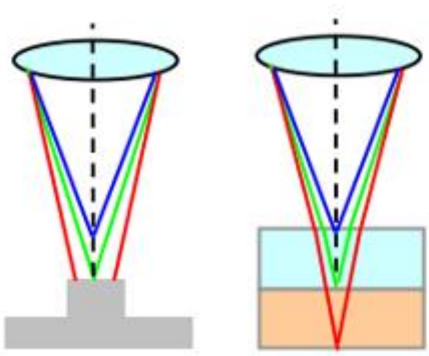


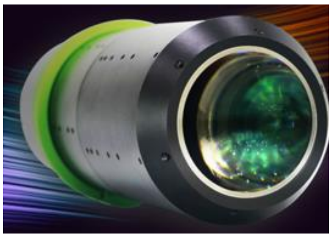
ILLUSTRATION 2.4 Confocal Displacement Method ([8], Keyence, 2020: P.1-28)

2.2 Benchmarking

Based on the literature review on various working principles and methods mentioned before, we have researched the state-of-the-art industrial solutions for thickness measurements. The current products generally apply the magnetic and the eddy current methods in portable, handheld thickness gauge carried by workers for rough measurements, inconsistent with our customer's requirements and working scenarios. Therefore, our survey concentrates on the remaining two methods: the ultrasonic and confocal displacement methods. We have chosen three specific products and acquire their particular engineering specifications to evaluate their feasibility for our purpose.

We have found the three products: USMX 200 ultrasonic thickness gauge made by a German company called MeSys ([6], MeSys, 2018: P.1-2) in ILLUSTRATION 2.5 (a), confocal displacement sensor D35 made by a Chinese company called LightE Technology ([7], LightE Technology, 2020:P.1-12) in ILLUSTRATION 2.5 (b), and a similar type of sensor CL-P015N made by a Japanese company called Keyence ([8], Keyence, 2020: P.1-28) in ILLUSTRATION 2.5 (c) respectively. The working principle of the first product is based on the ultrasonic method, while the latter two are based on the confocal displacement measurement. Their principles have been explained in the literature review.

a) MeSys USMX 200



b) LightE D35

c) Keyence CL-P015N

ILLUSTRATION 2.5 Three Products for Benchmarking

Of all engineering specifications of the sensors, we have chosen the six most important ones to investigate: range, resolution, linearity, frequency, spot diameter, and cost. The "range" represents the maximum measurable thickness and, in our scenario, should be at least 100 μm, which is the approximate thickness of the electrode sheet. The "resolution" refers to the minimum detectable interval, which should be smaller than 0.5μm required by our customer. The "linearity" means the average deviation of the measured values with the actual ones, identical with "accuracy" in daily context. Finally, the "frequency" is positively related to the sampling rate, and we use "spot diameter" to quantify the spatial resolution of the device. Although there are no requirements for the engineering specifications other than resolution, we believe that these are essential parameters for better measurement.

The detailed engineering specifications of MeSys, LightE Technology, and Keyence are parallel in comparison. Since the digits are not intuitive for human beings, we tried to rank each specification of a particular product from 0 (totally inconsistent with our demand) to 5 (totally consistent with our demand) and visualize the result in a radar chart (ILLUSTRATION 2.6).

TABLE 2.1 Comparison of Current Engineering Solutions

	MeSys	LightE Technology	Keyence
Range (μm)	1000	4200	1000
Resolution (μm)	0.001	0.008	0.25
Frequency (Hz)	120	800~4k	1k~10k
Spot Diameter (μm)	5000	8.1	38
Linearity (μm)	0.5	0.2	0.41
Cost	Very High	Low	High

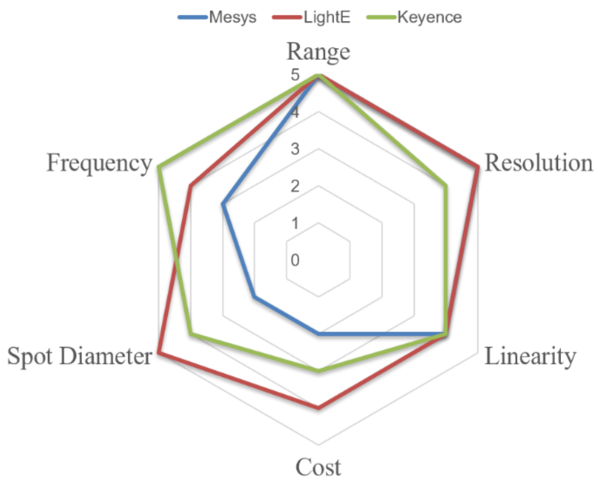


ILLUSTRATION 2.6 Radar Chart of Current Engineering Solutions

2.3 Customer Requirements

As mentioned in the introduction, the sponsor requires an alternative to the current measurement device. The alternative must be less expensive than the current one and have acceptable linearity, resolution, and repeatability between measurements. As we deploy the device in the factory in the future, the design's safety and flexibility should also be of paramount importance.

Furthermore, the device should be designed to manufacture and assemble with ease to reduce costs and grant the possibility of mass production.

Finally, as one of the key components in smart manufacturing, coupling with software is crucial. If possible, we should also consider the durability of the device. The customer requirements are listed below in TABLE 2.2.

TABLE 2.2 Summary of Customer Requirements

Customer Requirements
Low Cost
Good Resolution
Flexibility
Acceptable Linearity
Reliability (software)
Convenience
Safety
Good Manufacturability

2.4 Engineering Specifications

We have derived our engineering specifications from customer requirements. Emphasized by our sponsor, the low cost is the most crucial feature. The total budget is set to be lower than 100,000 RMB, much cheaper than the current option. The following engineering specifications (ES) can be divided into mechanical design and software design.

For the mechanical part, both the C-shaped frame designed to hold the sensor and the sensor itself contribute to the final result. The sponsor requires resolution to be lower than 0.5 µm. The linearity, using the current device as a benchmark, is 1µm. For more accurate results, the sampling frequency should be high enough. Tentatively, we set the frequency to be larger than 1000 Hz, but the determined value will be decided during tests to achieve the optimal result. The length of the frame is restricted to 500 mm so that it can fit into the factory's narrow space. The frame's weight should also be considered portability when we move the prototype between factories and laboratories.

Finally, the vibration of the frame's tip should be mitigated as much as possible to ensure a more accurate and consistent measurement. Therefore, the amplitude of vibration is another important specification.

For the software part, reliability is vital because one cannot afford an hour-long breakdown in the factory. Based on reliability, we should consider the convenience of using our software so that workers and engineers in the product line can operate the system without overwhelming training. A complete list of engineering specifications is summarized in TABLE 2.3.

TABLE 2.3 Summary of Engineering Specifications

Engineering Specifications	Target Values
Resolution	0.5 μm
Cost	<100,000 RMB
Reliability	pass MSA
Frame length	<500 mm
Sampling frequency	>1000 Hz
Vibration amplitude	<3 μm
Linearity	2 μm
Reliability (software)	high enough
Weight	<100 kg
Life to failure	>5 years

2.5 Quality Function Deployment (QFD)

As shown in ILLUSTRATION 2.7, customer requirements are converted to engineering specifications using QFD. The weight of and correlation between each specification are also summarized.

The low-cost requirement is related to the cost. Maximum displacement and size also relate to the cost because it determines the product's material and manufacture.

For the resolution part, accuracy slightly contributes to it because these two parameters will typically improve simultaneously. The length of the C-shaped frame can also be crucial as the vibration is dependent on it.

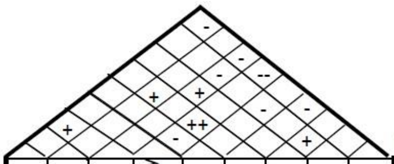
The extended measurement range is related to resolution because, within the budget level, these two parameters cannot be fulfilled.

Good software can be traced to resolution, sampling, and cost. First, resolution can be improved via filtering, which is viable through software. Cost in the form of labor costs must also be ensured to get good software.

Safety is attributed to the weight and size of the product for obvious reasons. Average life to failure must be ensured to prevent early failure in the factory.

Manufacturability and stability have something to do with nearly every engineering specification.

It is evident from QFD that cost, sampling frequency, accuracy, and resolution are the four most essential specifications we should pay attention to during the design process. That is to say, they are the CTQ ESs and serve as constraints in our designs. Sampling frequency and cost are given absolute priority when the sensor is selected. Only after targets set for these two specifications are met, accuracy and resolution will be considered. Low scores of other specifications mean that we have some design freedom to satisfy the target value.



	Weight (1-10)	average life to failure	resolution	holding frame length	measurement frequency	max. displacement	accuracy	weight	size	cost	*Mesys*	*Keyence*	*Light E*
											Benchmarks		
low cost	10					3			1	9	1	1	4
good resolution	9		9	1	9		3		1		4	4	2
long measurement range	7		3		9						4	3	2
flexible supporting mechanism	8		1	9	9		1	3	3	3	2	3	2
good software	6		3		3		9		1	3	2	4	2
safety	7	3						9	3		4	5	4
manufaturability	7	1		3	3	3	9	3	3	9	2	4	4
stability	8	9			3	3	3		1	1	4	3	3
Measurement Unit		yrs	µm	mm	Hz	µm	µm	kg	m^3	rmb			
Target Value		6	2	500	5000	1	1	20	1	50k			
Total		100	128	102	279	75	176	108	99	203			
Normalized		0.08	0.10	0.08	0.22	0.06	0.14	0.09	0.08	0.16			

ILLUSTRATION 2.7 Quality Function Deployment of the Project

We know that cost is almost always negatively correlated with other specifications from the correlation between engineering specifications. Therefore, we must make sacrifices in other specifications to ensure an acceptable cost. Other than the cost, the remaining engineering specifications are generally positively correlated with each other. This discovery proves the feasibility of our plan to build a measurement device with the required features.

Finally, some benchmarks are rated in terms of customer requirements. We see that cost and other requirements cannot be achieved simultaneously. This fact will play an essential role in our design and manufacturing.

Chapter 3. Concept Generation and Selection

3.1 Concept Generation

After determining the ES and QFD, our target is to generate the concept of the thickness measuring system that we would like to construct. First of all, since it is a system, we should figure out the overall frame of the system and the function we want to implement with this frame. After the initial brainstorming, we determined that the system should be composed of two parts: the hardware and software parts, as shown in ILLUSTRATION 3.1.

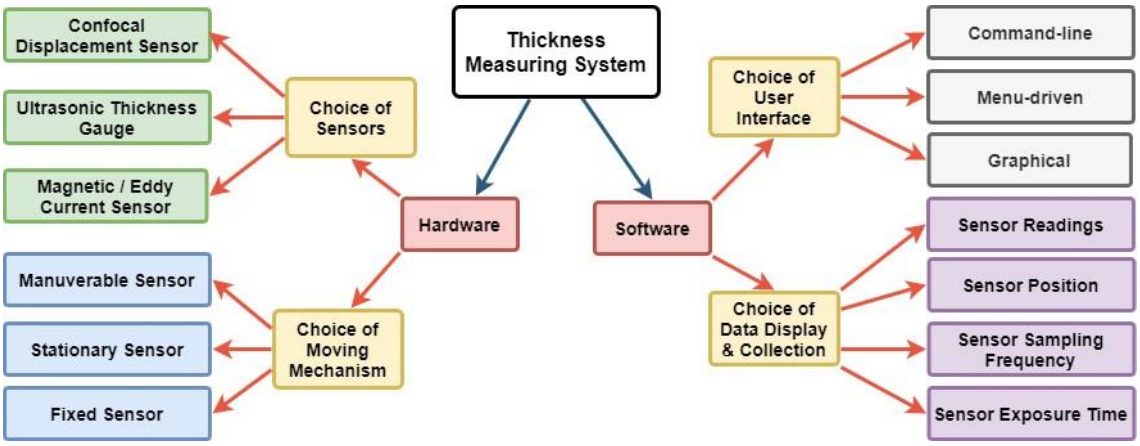


ILLUSTRATION 3.1 Conceptual Diagram of the Project

For the hardware part, there are also two steps to form the conceptual design: the first step is to decide which sensor we should use, and the second step is to find which mechanism we should use to implement the movement of the sensors.

Similarly, we need to determine the type of user interface we should use and the kinds of data and parameters we should collect from sensors and display to users for the software part.

After having constructed the basic frame of the system, the next step is to determine the function of each part to fulfill the engineering specifications and customer requirements. According to the conceptual diagram in ILLUSTRATION 3.1, we have identified the function for the sensor part, frame part, and software part separately. Generally, the sensor part is responsible for thickness measurements, the frame part is responsible for the maneuverability and stability of the sensors, and the software part is responsible for data processing and visualization. The detailed functions for each part of the thickness measuring system that we have brainstormed are listed in the functional decomposition diagram as follows in ILLUSTRATION 3.2. Here are the designed functions for each component of our thickness measuring system. Since the design should meet the function we need, the conceptual selection should be based on the instruction of this diagram

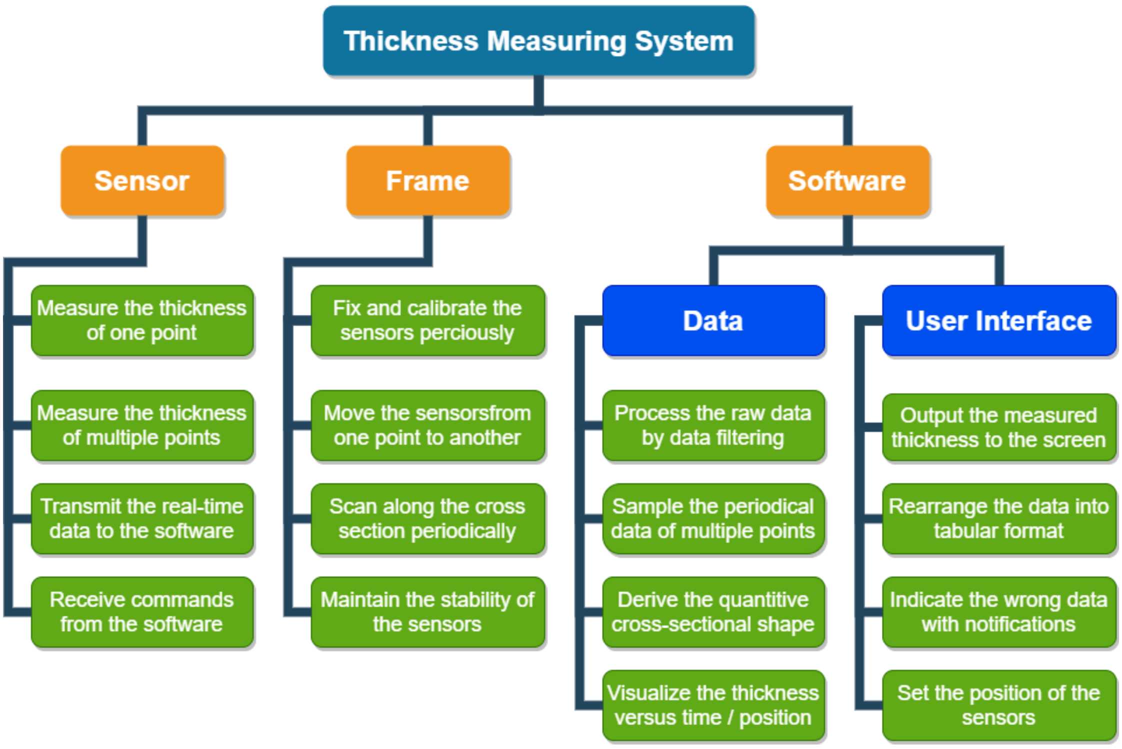


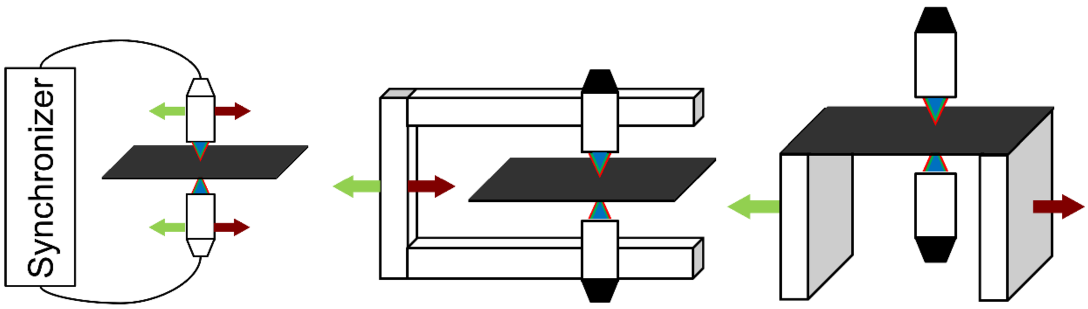
ILLUSTRATION 3.2 Functional Decomposition Diagram for the Project

3.1.1 Sensors

Based on our previous benchmarking results, it is not difficult for us to brainstorm several competing products, including the supersonic thickness gauges, the magnetic/eddy current sensors, and the confocal displacement sensors. We have prepared the information regarding brands (including Keyence, LightE, DeFelske, Fischer, QNix, and Beijing Time), models, and critical parameters (like resolution, range, the diameter of spots, price) for the selection procedures for each category of the sensors.

3.1.2 Moving Mechanism

We have come up with three design concepts: the first one is to make both sensors maneuverable (a). The sensors are driven individually by a separated mechanism, and their movements are synchronized and aligned by control algorithms. The second one is to fix the sensors on a frame to remain relatively stationary of sensors and the frame (b). In that case, when we need to move the sensor(s), we move the frame instead. The third method is to fix the sensors to the environment and move the conveying belt (c). It means that the sensors are stationary to the ground, and the relative movement of sensors is conducted indirectly by the conveying belt. Here is the illustration of the three kinds of moving mechanisms in the diagram below in ILLUSTRATION 3.3.

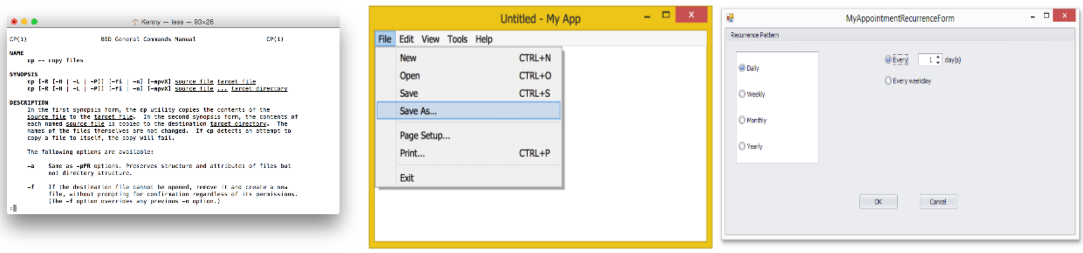


a) Maneuverable sensor **b) Stationary sensor** **c) Fixed Sensor**

ILLUSTRATION 3.3 Three Sensor Moving Mechanism Designs

3.1.3 User interface (UI)

For software concept generation, the first step is to select the appropriate user interface. Based on what we learned in software engineering courses, there are three distinct user interfaces: command-line user interfaces, menu-driven user interfaces, and Graphical user interfaces.



a) Command-line UI **b) Menu-driven UI** **c) Graphical UI**

ILLUSTRATION 3.4 Three Types of User Interface

As shown in ILLUSTRATION 3.4, the command-line UI requires users to type in commands from a list of allowable commands. The menu-driven interface employs a series of screens, or “menus.” When a user makes a selection by tapping/clicking on the list format or graphics, it takes them to the next menu screen until they complete the desired outcome. An example of menu-driven UI is ATMs. The graphical user interface, or GUI, is the type of interface most people are the most familiar with. Users interact with GUIs via a mouse or trackpad and click on graphics or icons.

3.1.4 Data collected and displayed

The second step is to decide what types of data should be collected and displayed to users. The sensors have many readings and parameters, including sensor thickness readings, current sampling frequency, current exposure time, exposure range, current gain, heart time, peak waves, etc. Our mechanical device includes a C-shape frame and its movable mechanisms. They also have many properties like position, speed, and vibration status. Furthermore, rollers in the product line also have properties like linear speed, angular velocity, and weight. What end-users need to know becomes one of our design problems.

3.2 Concept Selection Process

3.2.1 Sensors

As required by the sponsor, the measurement resolution should be as good as ±0.5mm. From II.i.a, we know that the resolution of the magnetic method is usually 3%, with the fact that the thickness of the electrode sheet is around 165μm, the target resolution cannot be met with the magnetic method. The eddy current method is also not suitable since the coating contains lithium substances that can catch fire.

Thus, only two methods that reach the target resolution are applicable in our project: the ultrasonic and confocal displacement methods. For the ultrasonic method, the MeSys USMX 200 is a mature solution. For the confocal displacement method, we have Shenzhen LightE and Keyence have existing solutions. Then the selection process focuses on cost. Among these three sensors, Shenzhen LightE Technology produces the most inexpensive sensors. Therefore, LightE D35 confocal displacement sensor is finally adopted by us.

3.2.2 Moving Mechanism

To compare three possible moving mechanisms of the sensor, we use the selection matrix to get numerical results. Criteria are generated following the customer requirements and engineering specifications. Weights are given to each criterion according to the initial weight shown in QFD. We see stationary sensor as the best possible solution by considering all criteria as shown in TABLE 3.1.

More specifically, the stationary sensor is acceptable in accuracy, stability, and manufacturability (ease to build) and outstanding in cost, reliability, and size compared to another two options.

TABLE 3.1 Selection Matrix for Different Moving Mechanisms

Type		Maneuverable		Stationary		Fixed	
Criteria	Weight	Score	Rating	Score	Rating	Score	Rating
Stability	0.25	2	0.50	3	0.75	4	1.00
Accuracy	0.12	3	0.36	3	0.36	3	0.36
Ease	0.10	1	0.10	3	0.30	4	0.40
Cost	0.25	2	0.50	3	0.75	2	0.50
Reliability	0.08	1	0.08	4	0.32	2	0.16
Size	0.20	3	0.60	4	0.80	1	0.20
Total		2.06		3.28		2.62	

As mentioned in the previous sections, the cost is the CTQ ES set as a constraint. It thus has a high weight of 0.25. The stationary option cost is lower than the fixed one because it takes less material to build a functional prototype. While the maneuverable option needs an extra synchronizer to make sensors coaxial, stationary, one utilizes its geometry to achieve the same effect, thus saving extra money.

The stability is another CTQ ES. It also weighs 0.25. In this case, the fixed option has the advantage for obvious reasons. The stationary option is also acceptable for us. In comparison, the maneuverable one is not ideal.

The potential size using the corresponding moving mechanisms is also considered and given a relatively high weight due to practical constraints in the factory. The fixed one is the worst as it requires a relatively large space to fit in the whole device.

Stationary one tops the three choices as it can be realized using a C-shaped frame, which accounts for a fraction of the space if using the fixed option. Maneuverable one is also acceptable in terms of size.

Finally, the other three criteria are also listed and given lower weight owing to their lower priorities in customer requirements. Their scores are given for evident reasons, so the reasoning will not be detailed here.

In all, the stationary sensor has obvious advantages compared to the other two moving mechanisms for our purpose.

3.2.3 C-shaped Frame Design

After the moving mechanism has been chosen, details of the design need to be further selected. As mentioned in the previous section, two options of the C-shaped frame are considered. We have made another selection matrix to compare them.

TABLE 3.2 Selection Matrix for C-shaped Frame Design

Type		Design 1		Design 2	
Criteria	Weight	Score	Rating	Score	Rating
Stability	0.25	3	0.75	5	1.25
Accuracy	0.12	3	0.36	3	0.36
Ease	0.10	4	0.40	4	0.40
Cost	0.25	3	0.75	3	0.75
Reliability	0.08	3	0.24	5	0.40
Size	0.20	3	0.60	3	0.60
Total		2.70		3.76	

Since the accuracy, cost, size, and manufacturing difficulty are comparable for these two options, we have entitled them with identical scores. To better get a sense of which one is better overall, we need to know the scores of other criteria. Without manufacturing and doing experiments, we simulate the normal working conditions of both C-shaped frames using finite element analysis (FEA). The simulation was run in ANSYS Mechanical R2021. A representative simulation result is shown in ILLUSTRATION 3.5.

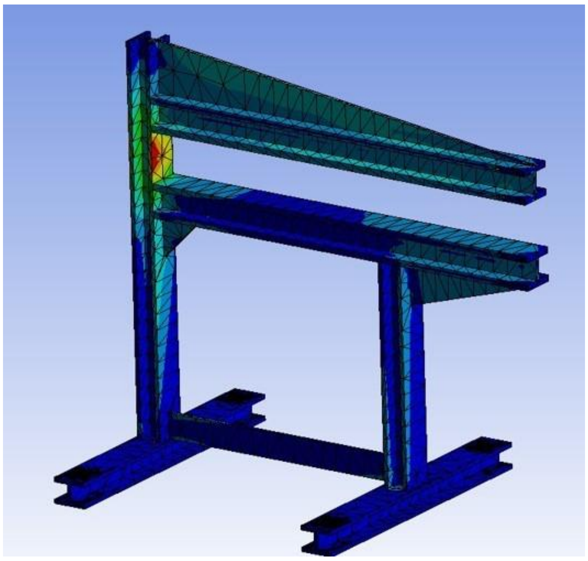


ILLUSTRATION 3.5 FEA Results (stress) of a Moving C-shaped Frame

After calculation, Design Two is selected. The reasoning for stability and reliability is detailed as follows.

3.2.4 Stability

Under working conditions, a C-shaped frame moves from one spot to another and stops to measure one point's thickness. Therefore, it is crucial to quantify the stability of the structure when it reduces its velocity to zero. The input velocity profile is shown in ILLUSTRATION 3.6.

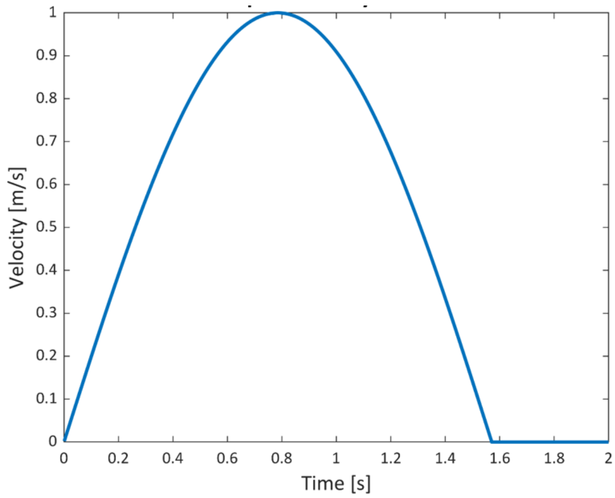


ILLUSTRATION 3.6 Simulation Velocity Profile

The result is shown in ILLUSTRATION 3.7. It shows that Design Two has better stability than Design One because its amplitude of vibration dies out much faster than Design One. Therefore, the score of stability of Design Two is higher than Design One in the selection matrix.

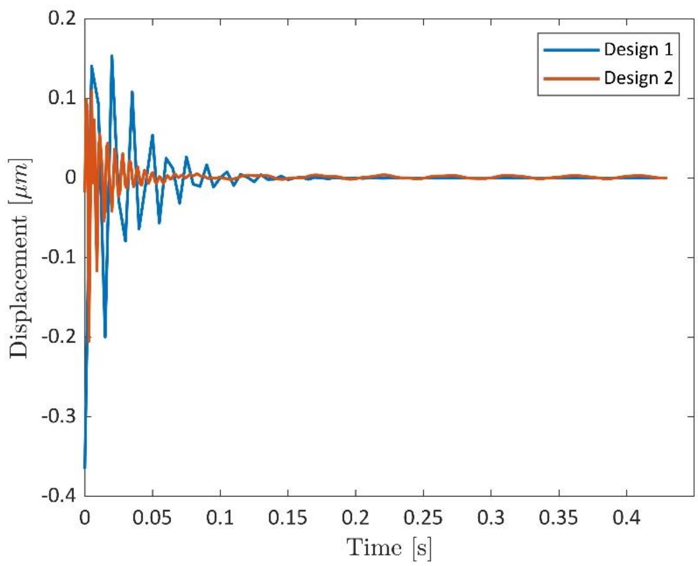


ILLUSTRATION 3.7 Vibration About the Equilibrium After the Frame Stops

3.2.5 Reliability

To compare the reliability of the two options, we impose harmonic oscillations on frames and extract the maximum stress at each moment. As delineated in ILLUSTRATION 3.8, Design One has a much higher average maximum stress than Design Two. Therefore, it is more likely to fail due to fatigue as we know

$$\tau_{avg} \propto \sigma_{max},$$

where τ_{avg} is the average life before failure and σ_{max} is the maximum stress for cyclic stress patterns. In conclusion, the reliability of Design Two is better owing to its longer predicted life before failure.

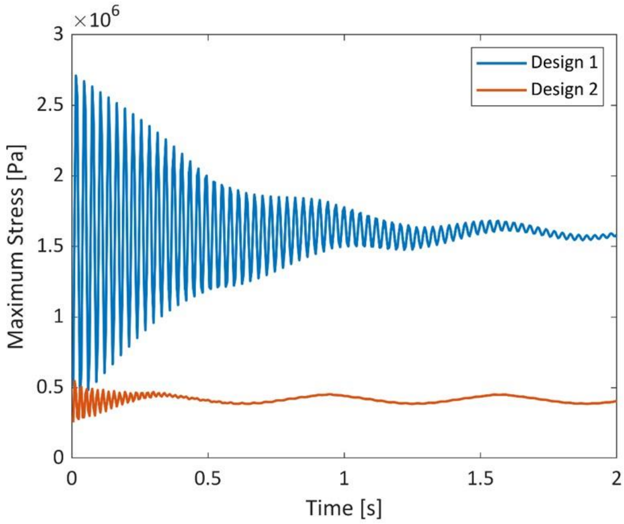


ILLUSTRATION 3.8 Max Stress during Harmonic Oscillations

3.2.6 User Interface Design

After discussions with the sponsor, we get to know the intended end-users of the prototype are workers and engineers in the factory, who are not likely to have programming experience. Therefore, our user interface should be simple, neat, and convenient to use. Since command-line UI requires some basic programming knowledge, our intended end-users might need to learn console commands before using a command-line UI, which is unacceptable. Therefore, the idea of using the command lines is dropped.

Then we need to choose between menu-driven UI and graphical UI. Both of them are self-explanatory and simple to use by novices. Furthermore, we have also found lots of industrial software of each type. Finally, we realize one feature of our prototype is to monitor current measurements while recording data if needed continuously, which means two functions (monitor + record) need to work on the same page simultaneously. It is tough to implement such features in a menu-driven user interface, in which users can only select one button in a menu screen until they complete the desired outcome.

3.2.7 Data Collected and Displayed

After the type of user interface is selected, we need to select the types of data our system should read and display to end-users. To determine that, we need to understand how the data will be used. After discussions with our sponsor, the data collected will be used to evaluate the working conditions of the coating process and improve the coating quality. Therefore, the data collected should be closely related to thickness and positions.

For sensors, their distance readings are the most critical data we need. Besides, it is also critical to know where the measurement occurs. So, the sensor position, which can be calculated from the C-shaped frame position, is needed. We can only locate the measurement on one axis with a sensor position perpendicular to the product line. We also need to get the location along the product line. Therefore, we also need a real-time speed of rollers to locate real-time belt positions. In the actual product lines, the speed of rollers can be read from other industrial software. In this project, we assume the speed of rollers can be read from an external interface to set a constant value for roller speed. Lastly, the timestamps of the measurements should be recorded as a reference.

3.2.8 More Considerations

In this section, we discuss what we would have done under an ideal situation. By an ideal situation, we assume that we knew the entire picture of the project, which includes all the difficulties and changes in customer requirements, by the time we generate our concept.

3.2.8.1 User-friendly Hardware

While we did consider the software's user-friendliness, we hardly considered the operation of the hardware. Throughout the assembly and the test, we found some limitations that we could have avoided in the first place. For example, calibration of sensors can be hard for novices. The calibration itself is lengthy, and the lack of or insufficient helping mechanisms does not help either. It took us about one week to master the skill of calibration. Because the hardware is expected to be operated by ordinary workers in the factory, we must make the whole process as easy as possible. It is not realized by our current design as we did not put much emphasis in this regard. We would try to make this one of our priorities if we had another chance.

3.2.8.2 Time Management

As much as we have kept track of the project timeline and rectifying it whenever necessary, we still fell into some pitfalls along the way due to our lack of industry knowledge. The outstanding issue is the overly complicated design of the hardware. Since all structures and corresponding dimensions are customized according to our requirements, they have to be manufactured through particular processes, which cost more than one month to complete, which far exceeded our expectations. However, this is the usual time to manufacture a complicated and specially designed component for our sponsor. Therefore, if we knew the industry better, we will resort to an alternative way to solve this issue. For example, we might use standard components to redesign the hardware so that the manufacturing time can be significantly reduced. While the performance might not be as good as the original one, the trade-off is worthwhile as time is limited.

Chapter 4. Final design and implementation plan

4.1 Concept Overview

The thickness measurement system includes a hardware subsystem that achieves thickness measurement and displacement of the sensor system and a software subsystem that acquires, filters, visualizes, and transmits measured data and communicates with the user.

ILLUSTRATION 4.1 shows a rendering of the hardware system. The C-shaped frame in blue is designed to fix the sensors in green using the brown fixtures. It can also move along the two red slide rails to scan through the entire width of the electrode sheet driven by the rollers.

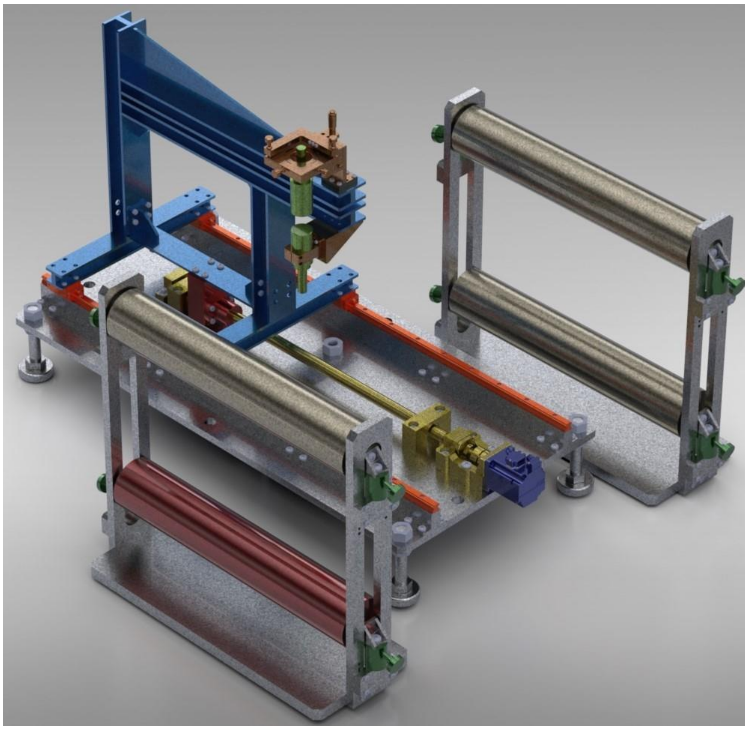


ILLUSTRATION 4.1 Rendering of the Hardware System

ILLUSTRATION 4.2 shows the up-to-date version of the graphical user interface (GUI), enabling the user to acquire and visualize the filtered data, i.e., the thickness of the electrode sheet. Via the software subsystem, the user can also calibrate the sensor and control the displacement of the C-shaped frame along the slide rails.

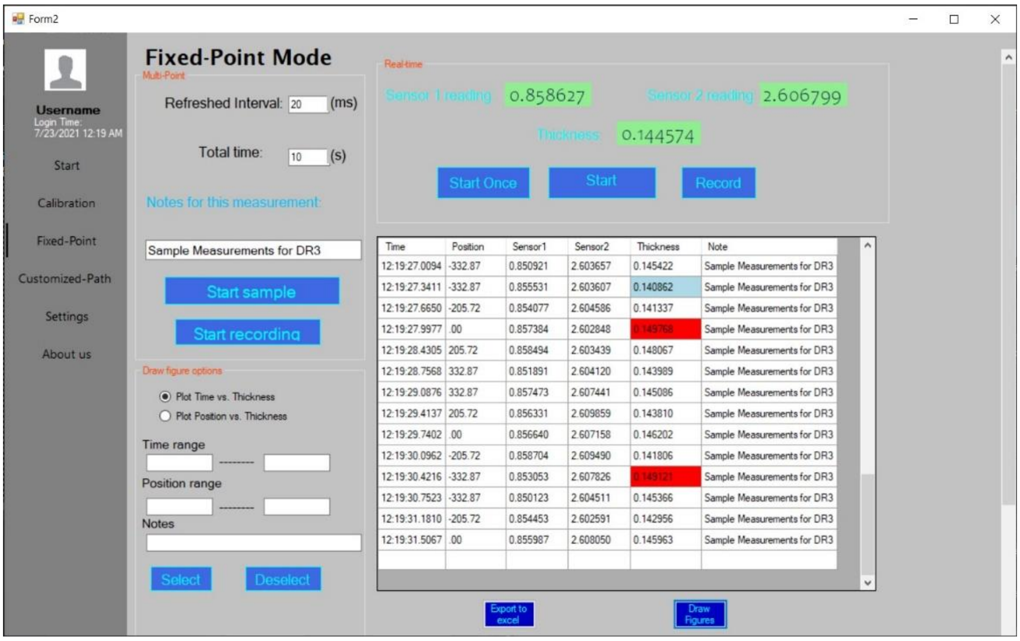


ILLUSTRATION 4.2 Screenshot of the Software in Light Theme

ILLUSTRATION 4.3 shows the flowchart for the operation procedures of the whole system. The red lines represent the data transmission from the server to the slave machines, while the blue lines represent the data acquisition from the slave machines by the server. Besides, the green line is the data exchange and calculation that happened inside the server. We can also identify the detailed contents of each data flow from the illustration. The flowchart reveals how our thickness measuring system works and the overview of the connection between the hardware and software parts of the system.

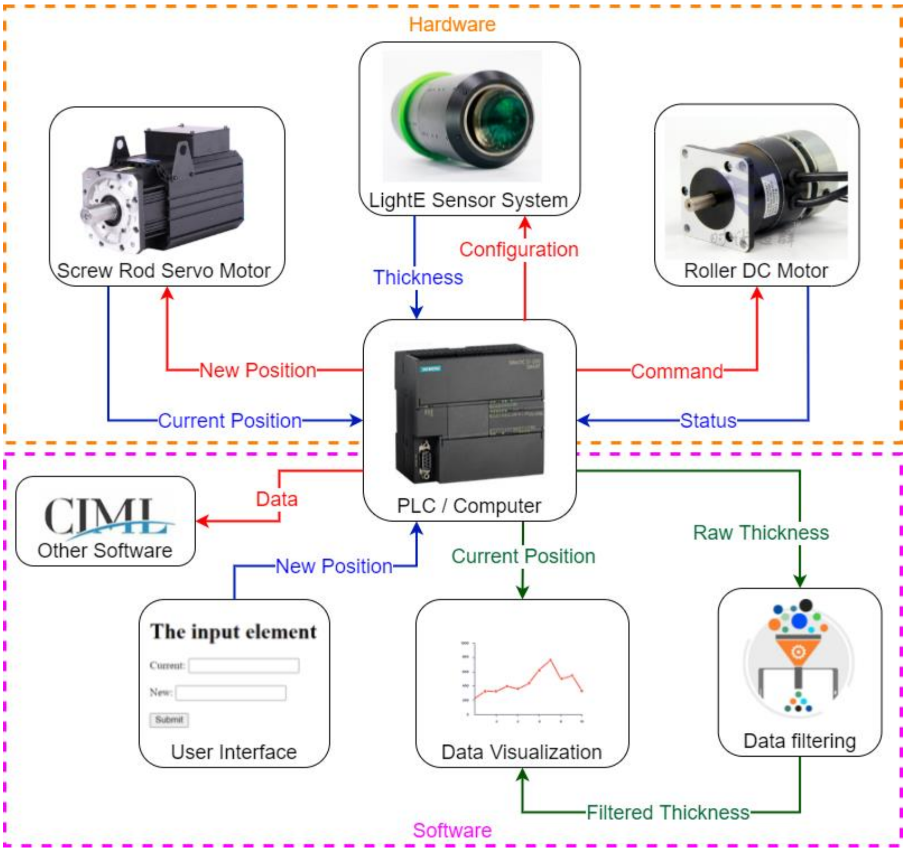


ILLUSTRATION 4.3 The Flowchart of the Thickness Measuring System

Overall, the expected performance of this design is that the resolution for measurements with static electrode sheet and sensors is ± 0.5 μm, with a size smaller than 1.5 m × 1 m × 2 m and cost less than 100,000 RMB. The prototype should also pass measurement system assessment.

The resolution is tested with multiple experiments with a systematical, standard method to validate our design. The details are to be discussed later.

4.2 Engineering Design Analysis

4.2.1 Hardware

Since the real world is complex and imperfect, it is not enough to manufacture the selected conceptual design. We have to modify many details of our design to balance the ideal design and actual products to meet requirements. According to the engineering specifications, the linearity of our measuring device should be less than 1μm, which is a hundred times thinner than the diameter of the hair. Also, since the confocal distance sensors we have chosen rely on the reflected light, the fluctuation of the C-shaped frame should be eliminated to ensure the consistency of the light detection process. Therefore, our device should be highly stable to resist the effect of ubiquitous vibrations. To fulfill this requirement, we have made some unique designs for our product.

ILLUSTRATION 4.4 shows that we have designed two guide rails and four slide blocks for the C-shaped frame on the baseboard. If we want to move the frame, we have to exert force on it. Compared with the biped animals (like humans), the tetrapod animals (like a horse) resist the suddenly exerted force because the center of gravity lies between the front and back legs. Similarly, the C-shaped frame we have designed is tetrapod to enhance stability while it is driven by the guide screw underneath.

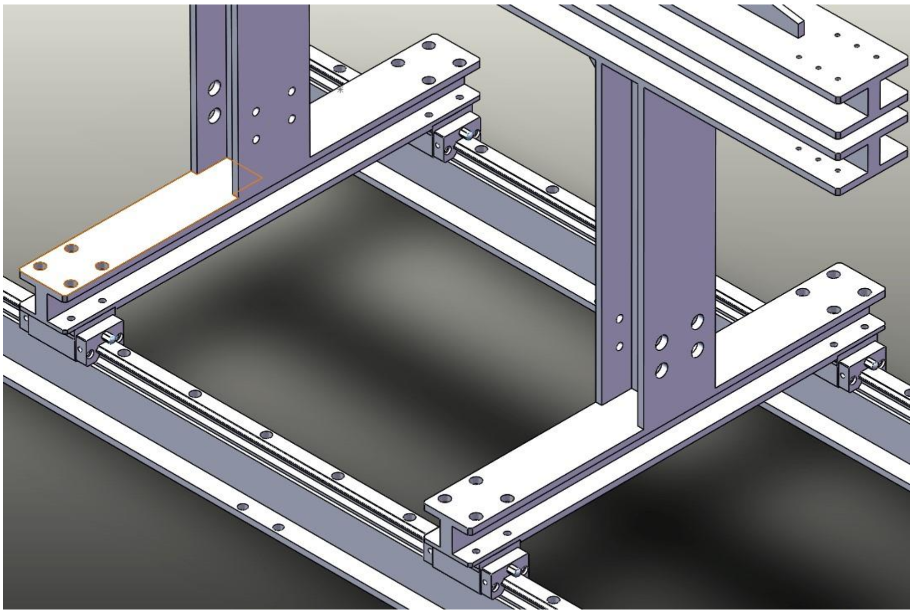


ILLUSTRATION 4.4 The Tetrapod Design of C-shaped Frame

Also, in ILLUSTRATION 4.5, we have added some ribs at the corners of the adjacent beams. The principle is to increase the contact area between the beams. According to the knowledge of structural mechanics, with the same exerted force, the displacement at the beam's moving end is inversely proportional to the contact area at the fixed end. Therefore, adding ribs at the corners can significantly reduce the deformation of beams and consequently eliminate the fluctuation at the tips where the sensors are installed.

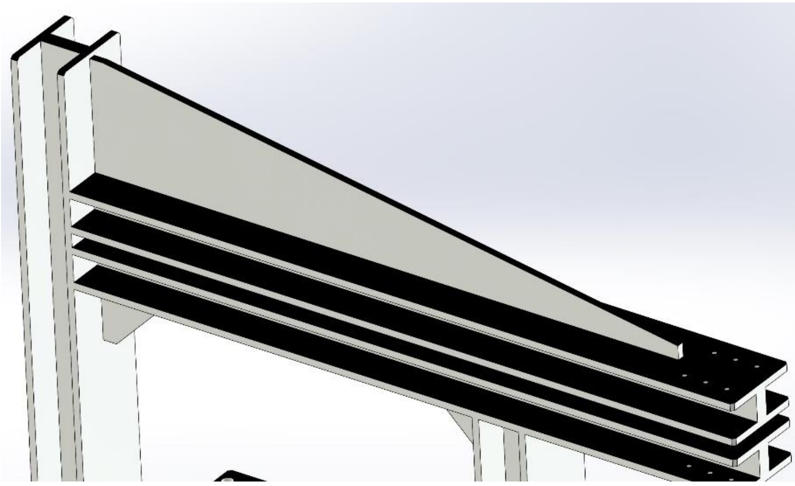
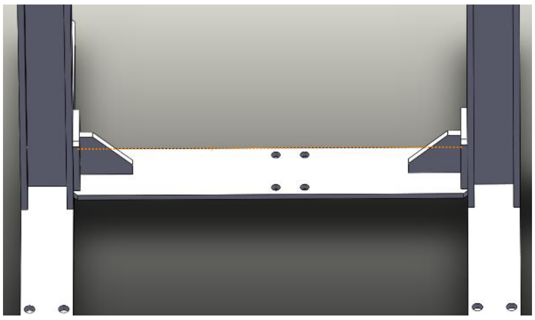
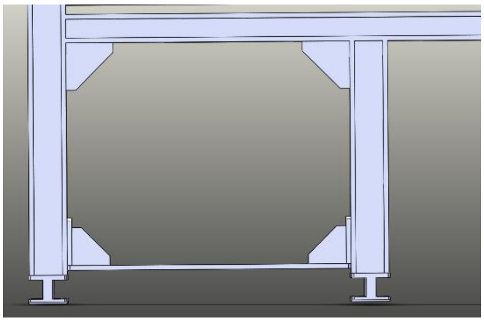


ILLUSTRATION 4.5 The Ribs at the Corners to Enhance Stability

Moreover, at the bottom of the C-shaped frame, a central beam is shown in ILLUSTRATION 4.6 (a). Without it, we can see from the side view that the C-shaped frame is an open structure formed by three edges. Considering the continuous payload and sudden driven force exerted on the frame, the reliability of this open structure is not guaranteed. As a result, we have added a central beam to make a vertical, closed structure with enhanced reliability, as shown in ILLUSTRATION 4.6 (b). Also, we have designed the central beam as the intermediate platform to mount the C-shaped frame with the guide screw.



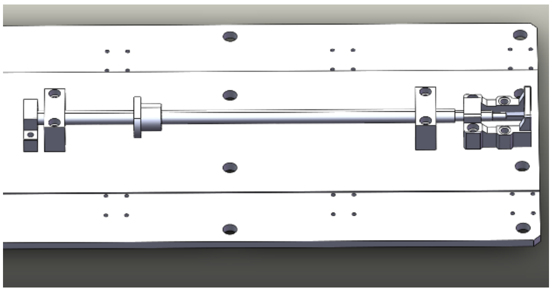
a) **The extra central beam**



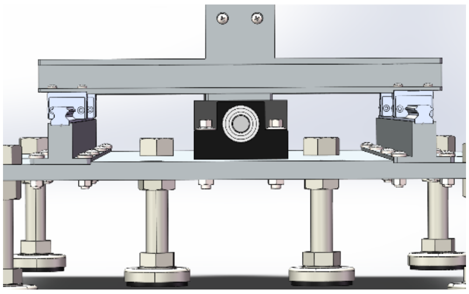
b) **The side view of the frame**

ILLUSTRATION 4.6 The Details of the Central Beam

Speaking of the guide screw, we have made it co-linear with a symmetry plane of the C-shaped frame to get rid of the potential torque whose direction is perpendicular to the platform in ILLUSTRATION 4.7 (a). Also, the joint block between the upper frame and the lower guide screw cap is deliberately positioned at the center of gravity of the C-shaped frame rather than the middle point of the central beam (which you can see in ILLUSTRATION 4.7 (a). Besides, the guide screw is hidden under the whole frame to avoid potential interference and save space, reducing the size of our device shown in ILLUSTRATION 4.7 (b). To achieve this, we have specially designed the guide rail installation platforms to lift the slide blocks and give room to the guide screw sets. Here is the perspective from the front view clearly in ILLUSTRATION 4.7 (b).



a) **The guide screw set**



b) **The guide screw lies under the fram**
e

ILLUSTRATION 4.7 The Details of the Guide Screw

Last but not least, all beams that we have used to make the C-shaped frame are I-shaped for their cross-sections (ILLUSTRATION 4.8). Such design is the compromise of weight and strength. Had the beams were all solid square-shaped for cross-sections, the total weight for our C-shaped frame would be too large to be driven. If we use the hollow square-shaped beams, the strength of our structure would not be enough to resist the bending effect and diminish vibration to fulfill our requirements. Therefore, we choose the I-shaped beams to compromise strength and overall weight.

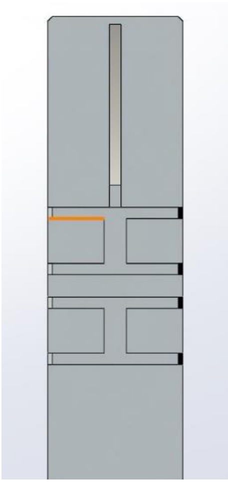


ILLUSTRATION 4.8 The Cross-section of the I-shaped Beams

4.2.2 Software

Though most customer requirements and engineering specifications are achieved in hardware, our software should help with reliability and convenience in customer requirements and sampling frequency and reliability in engineering specifications. Reliability is close to the research area of software performance and security. Convenience to use lies in the field of human-computer interaction. Furthermore, (accurate) sampling frequency is heavily related to synchronization since it involves sharing frequency across different platforms. Our software can support reliability from the following aspects:

- Bug-free codes

One way to support reliability is to make sure bug-free. Though it is almost impossible to keep so, we can test our software to make sure it works most of the time.

- Initialization

Unavoidably software will sometimes stop working, mainly when unusual user behavior happens, like clicking buttons too quickly or closing the windows when some threads are still running. Initializing key variables makes sure the application is running well when it starts over. Our software initializes every variable and uses only one project settings variable to guarantee that it is workable every time it starts.

Our software can support convenience to use from the following aspects:

- Detailed instructions

For the convenience of end-users and particularly first-time users, we provide detailed instructions on the first page of our software. It can help users quickly learn the features of our software and how to use them.

- Color theme

As shown in and, our software has two color themes, light and dark, to adapt to the different working environments.

- Flexibility to select

As shown in, we provide different ways for users to select which data they want in their plot.

For sampling frequency, users can easily modify it by setting new values of refreshed intervals. Our software will pass the user-defined value to the LightE sensor system to make sure both the sensor system and our software are recording data at the same frequency.

4.3 Design Description

4.3.1 Hardware

Referring to the design analysis process that we have just mentioned before, we can now do the concrete design of the parts that we would like to use in the device. The first step is to draw the CAD of the designed parts and identify the dimensions for further manufacturing. The detailed drawings are put in Appendix I, including the baseboard, the C-shaped frame, the fixtures for sensors, the connecting block between the C-shaped frame and the guide screw cap, the guide rail installation platform, and the extra central beam. Out of the confidential agreements, all the dimensions are concealed. Some other parts of our design are standard parts that can be brought directly from the vendors. TABLE 4.1 is a summary of their names, models, and pieces we have used. The complete list of components can be found in Appendix II.

TABLE 4.1 List of Standard Components Used for the Prototype

Name	Model	Pieces
Guide screw with a screw cap	LCS47-20-5-L700-F20-P10-LB	1
Guide screw set (supporting side)	LEB31-15	1
Guide screw set (fixed side)	LEF15-d15-F60-h30	1
Linear positioning stages	E-EIC61-40	1
Guide rail with two slide blocks	IBC03-H40-L700	2
Link stopper	BSTP20	2
Shaft coupling	DEG51-D33-d10-e14-DD	1
Servo motor	MS1H1-20B30CB-A331Z	1
Servo motor driver	SV660N-Size A	1
Foot cup	KC-280-60-4	6

4.3.2 Software

This section describes different features of our software and how they are connected. ILLUSTRATION 4.9 uses a flowchart to describe how typically people would use our software. First, users need to connect the LightE sensor system with the host computer and check whether the sensors are detected. Next, people can select either multi-point mode or real-time mode to take measurements and record data. After enough data are collected, people can have it plotted or exported into CSV files for further data analysis.

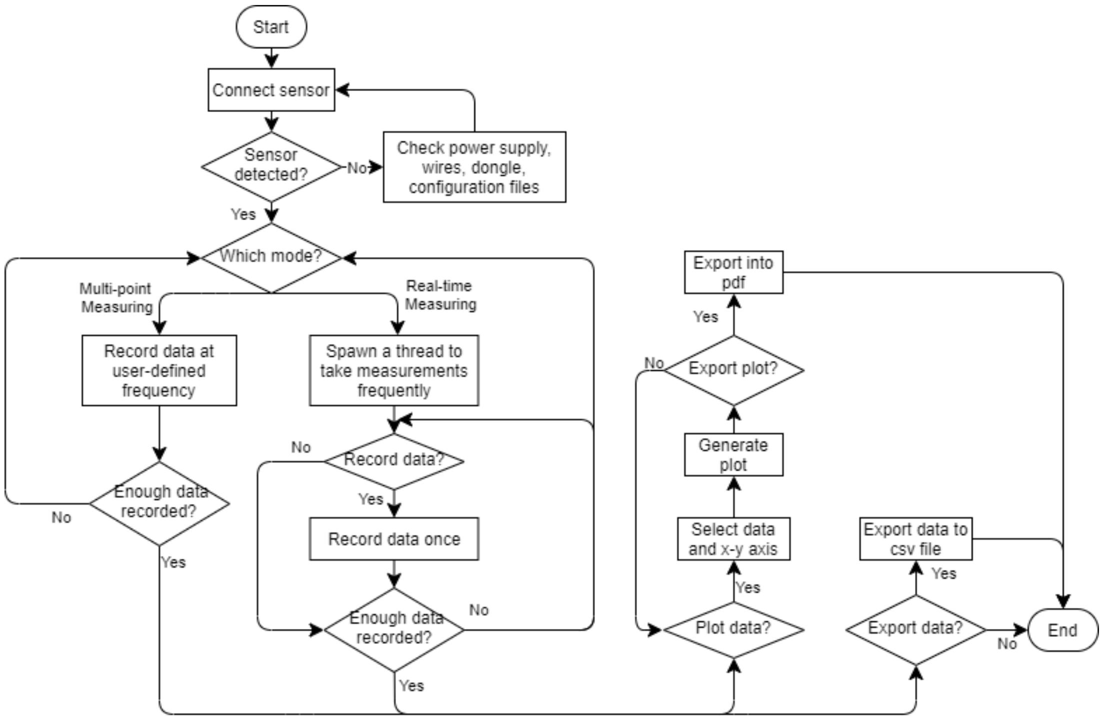


ILLUSTRATION 4.9 Flowchart of User Procedure

To connect our software with the sensor system, users must first select a DCFG file and an HWC file compatible with the sensor system. The sensor company provides these two files. If the connection is set up correctly, the number of devices connected should be 1, and the number of channels detected should be 2. This step is shown in ILLUSTRATION 4.10.

After the connection is set up, users can take measurements in 2 modes: multipoint and real-time. In multi-point mode, users select a refreshed interval and a total time. Our measuring system measures a user-defined frequency. The data will be recorded into the sheet on the right lower corner. In real-time mode, the real-time sensor readings are listed in the three green boxes. Users click on the "Record" button to record current readings into the sheet once. This step is shown in ILLUSTRATION 4.11.

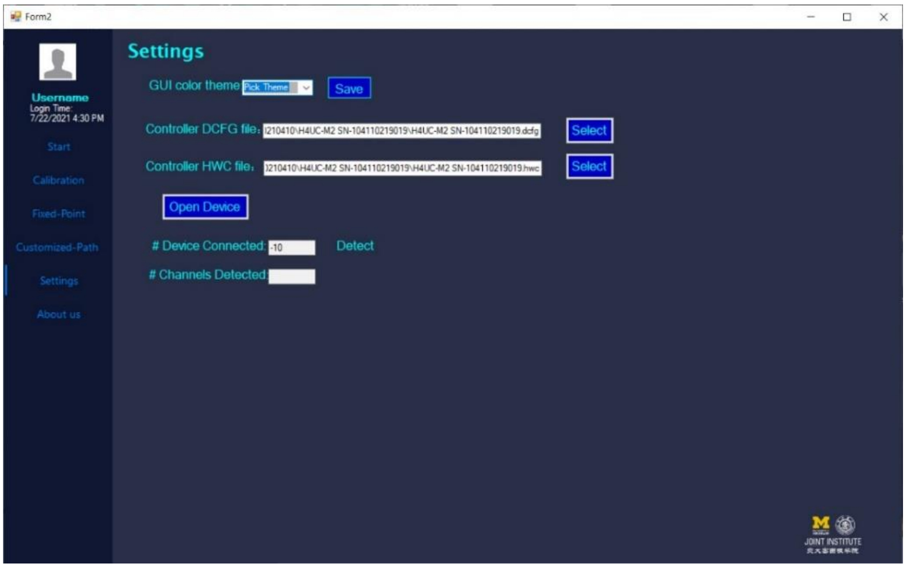


ILLUSTRATION 4.10 Screenshot of Settings

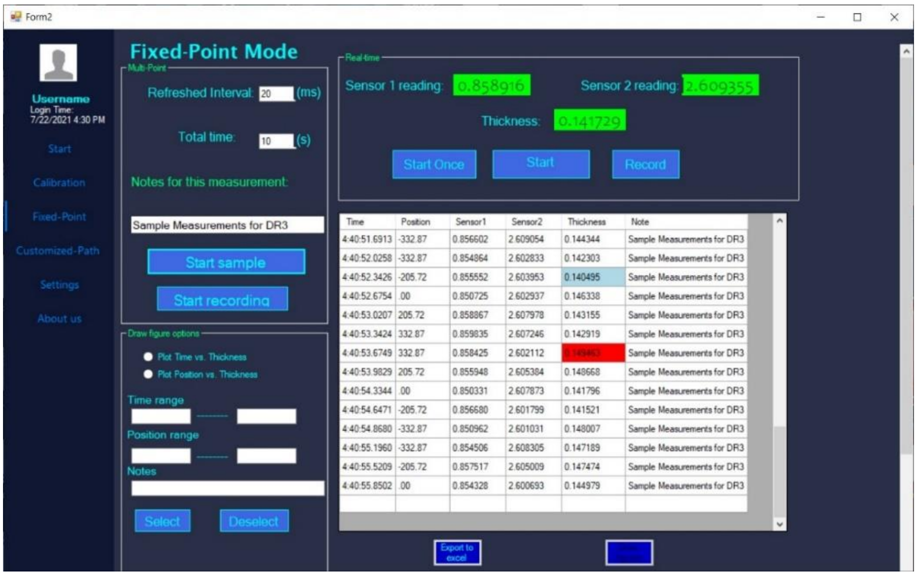


ILLUSTRATION 4.11 Screenshot of Fixed-Point Mode Data Collection

After all the data is collected, users can select specific rows of data to plot, either by directly choosing from the sheet or selecting groups of data via filters on the lower-left corner, as shown in ILLUSTRATION 4.11. Here are data filters, including time range, position range, and notes. Users can also select which plots they want, either time vs. thickness or position vs. thickness. After selecting all data needed, users can click the “Draw Figures” button to generate figures. A sample figure is shown in ILLUSTRATION 4.12.

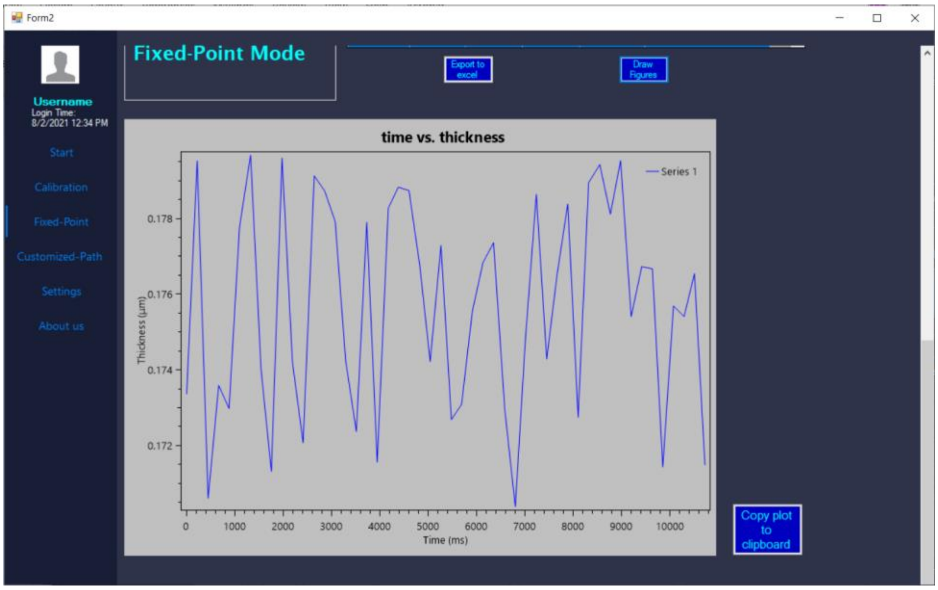


ILLUSTRATION 4.12 Screenshot of Fixed-Point Mode Data Visualization

4.3.3 Hardware Manufacturing

To manufacture the non-contact thickness measurement device prototype as designed above, the list of materials we would use is shown in TABLE 4.2. Most of the components are made of steel and are connected by screws and nuts. The complete list of components is in Appendix II.

The dimensional tolerance of holes with a diameter ≥ 5 mm is 0.5 mm, which is vital in assembling. For the two beams of the C-shaped frame, the geometric tolerance of parallelism of 0.08mm (as shown in red rectangle in ILLUSTRATION 4.13[1]) is essential, as the two sensors fixed to them need to be concentric, and this strict tolerance ensures acceptable assembly. For every component that is not a standard component, the surface roughness is 3.2 µm. Tolerances in holes whose diameter is < 5 mm are less critical since fitting between such holes and standard screws are always easily ensured. Geometric tolerances such as flatness of surfaces, the circularity of holes, perpendicularity within I-beams is less critical since they do not affect much in either assembling or functionality of the structure.

TABLE 4.2 List of Materials and Manufacturing Processes

Part	Material	Manufacturing process
baseboard	steel	cutting, drilling, milling
C-shaped frame	steel	drilling, cutting, welding
foot cup	steel and robber	standard component
lead screw	steel	standard component
lead screw support	aluminum, rubber	cutting, drilling
nuts	stainless steel	standard component
rollers	steel, rubber	standard component
roller support frame	steel	cutting, drilling
roller support	aluminum, steel	standard component
screws	stainless steel	standard component
slide rail support	steel	milling, drilling
slide rail	steel	standard component
sliders	steel	standard component

[1] The dimensions are confidential, and are thus blocked by black rectangles.

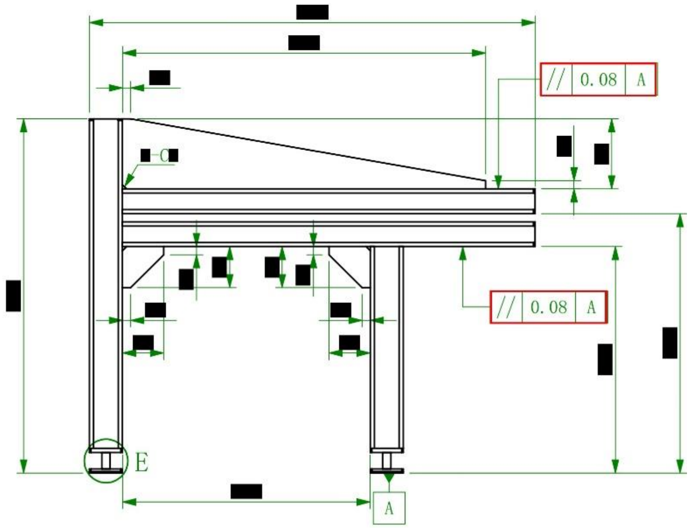


ILLUSTRATION 4.13 Geometric Tolerance of C-shaped Frame Highlighted in Red Rec tangles

4.3.4 Assembly Plan

The assembly process of the prototype consists of three parts: assembly of the baseboard, assembly of the C-shaped frame, and the overall assembly. First, the servo motor, the lead screw, two slide rail supports, and two slide rails are attached to the baseboard by screws and nuts, as shown in ILLUSTRATION 4.14.

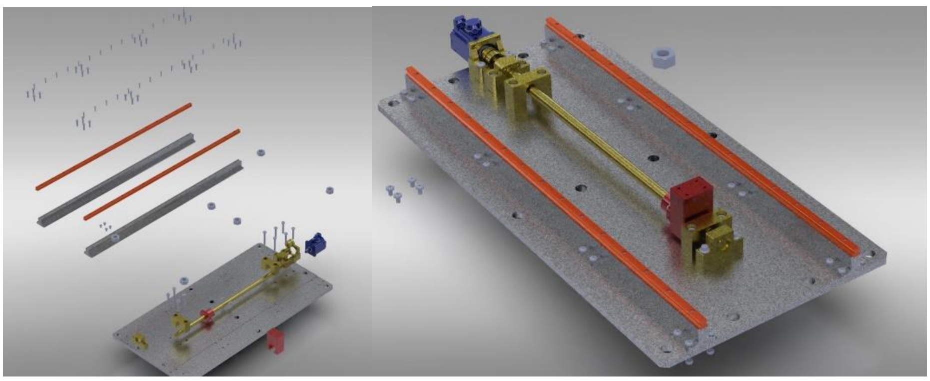


ILLUSTRATION 4.14 First Step of Assembly: Assembly of the Base Board (left: before; right: after)

Then the sensors, the sliders, and the central beam are assembled to the C-shaped frame with screws and nuts, as is shown in ILLUSTRATION 4.15.

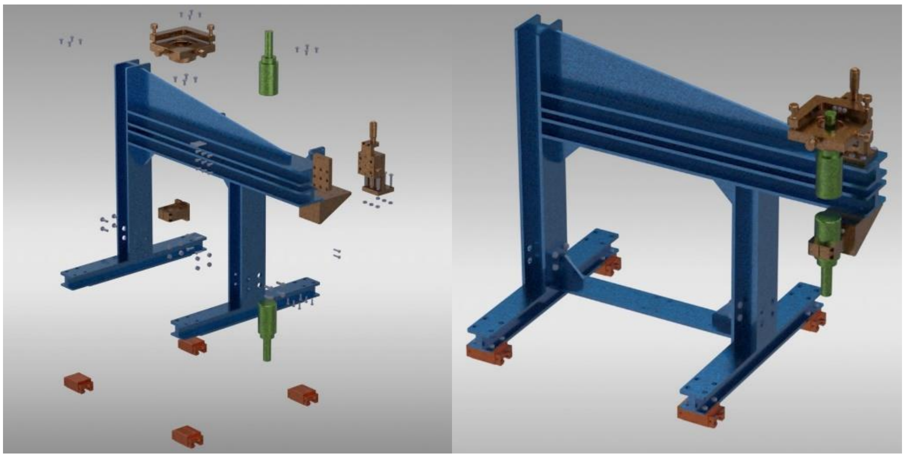


ILLUSTRATION 4.15 Second Step of Assembly: Assembly of the C-shaped Frame (left: before; right: after)

Finally, the two assemblies are assembled via the slide rail and the sliders, and six-foot cups are assembled to the baseboard, as is shown in ILLUSTRATION 4.16. Also, the rollers that simulate the electrode coating line in real factories are put together, as shown in the right part of the exact figure.

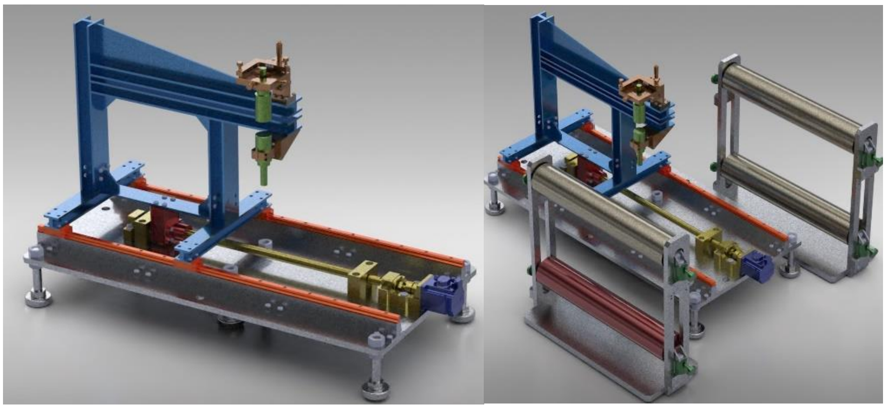


ILLUSTRATION 4.16 Final Step of Assembly: Assembly of the Overall Structure

4.3.5 Software Implementation

Our project is primarily a hardware project. However, according to our sponsor's request, a graphical user interface (GUI) is needed to control our measuring system considering the convenience of workers in the factory.

The goals of our software are 1) to connect sensors to PCs, 2) to take measurements as requested, and 3) to visualize and store measurement data. Details of our software development are listed below:

- Programming Language: We decided to implement our software in C Sharp (C#). It is because our sponsor, CIML, usually develops their software in C#. Moreover, they might build advanced features on top of our software. Besides, our software is intended to be running on the Windows platform.
- Software: We used Visual Studio 2017 as our IDE. Visual Studio is one of the most popular code editors for C# development. It has many built-in tools and plug-ins to make programming easy and enjoyable. Since we planned to build a Windows Forms App, .Net Framework was selected.
- Existing Source Code: Our sponsor purchased the Shenzhen LightE sensor system for us. Furthermore, together with the sensors, the sensor company also sent us a Software Development Kit (SDK) and corresponding manuals, which contains a C# demo program. We used part of this C# demo in our implementation.
- Libraries used: 1. The sensor SDK libraries as mentioned above. 2. Oxyplot libraries: a family of cross-platform plotting libraries for .NET applications.

4.4 Budget

The budget offered by the sponsor to build this prototype is up to 100,000 RMB. Most of the non-standard components are provided by CIML, and the expenditures paid by their budget are confidential and thus not provided here. The primary cost is on the Shenzhen LightE confocal displacement sensor system, which costs 60,000 RMB. All other components provided by the sponsor together cost less than 20,000 RMB. Therefore, the expenditure within CIML is fully covered by the budget. The budget offered by UM-SJTU Joint Institute is up to 4,000 RMB. We spent around 3,000 RMB on standard components such as screws, nuts, the power supply, the roller support frame, and other inexpensive components. Overall, the initial budgets are enough for all the tasks.

TABLE 4.3 List of budgets

Item	Price (RMB)
Sensor	about 60,000, provided by CIML
Sensor Clamps	provided by CIML
Sample Electrode Plate	provided by CIML
C-shaped frame, base board, slide rail	< 20,000 provided by CIML
24V Switching Power Supply	63
Copper Wires	145.96
Power Cables	30
Control Board	about 300
Motors	about 800
Other Mechanical Components	about 1500

Our budget plan is shown in TABLE 4.3. In this project, we need to build a prototype of our measuring system and a sample production line to demonstrate and examine its performance. A considerable proportion of our budget was spent on a confocal distance sensor system, bought by our sponsors and mailed to us. For a better demonstration of our prototype at Design Expo, a sample production line is also needed. Thus, a small proportion of our budget was spent building such a production line, including Sample Electrode Plate, Motors, and other necessary mechanical components.

Chapter 5. Validation Results

5.1 Evaluative Experiments

To verify that the target resolution of the system is achieved and the thickness measurement is stable, we need to conduct a couple of evaluative experiments.

1. Static evaluation of resolution: With the roller turning off, fix the position of the C-shaped frame and measure the thickness at some specific, static point on the electrode sheet at a constant frequency (4000 Hz). Plot the sensor data (Time vs. Thickness) and determine its range.
2. Measurement system assessment (MSA): With the rollers off, three persons measure the thickness of 4 positions of the electrode sheet three times per position. Calculate the range of measurements per trial per person. Calculate the Gauge Repeatability and Reproducibility (%GRR) value.

To sum up, the engineering specifications tested are listed below:

1. Resolution: ±0.5 µm,
2. Stability: pass MSA.

The plots of the experiments are listed in Appendix.

5.2 Explorative Experiments

As required by the sponsor, CIML, the resolution of this thickness measuring device should be as good as ±0.5 μm, which has been reached from the result of preliminary verification. The following exploratory experiments are conducted to alleviate both fluctuations in short terms (~ 1 s) and shift in long terms (~ 1000 s) in the measured data.

1. Observation: Fluctuations in short terms in electrode measurements are generally higher than those in white standard calibration block measurements.

Hypothesis: The electrode sheet is black and absorbs more light, resulting in a lower intensity of reflected light, which can be easily affected by minor noises.

Experiment: In an environment of no disturbance, no wind, and constant temperature, and with the rollers off, measure the thickness of the white calibration block at a constant frequency (4000 Hz) for 20 s, calculate the range, standard deviation and repeat for three times. Then in the same condition, measure the same calibration block that is the same in the previous experiment but is painted to black, at a constant frequency (4000 Hz) for 20 s, calculate the range, standard deviation, and repeat three times.

Result: Measurements of the calibration block printed to black have more significant fluctuations than the white counterparts. The color of the measured object does affect fluctuation.

Observation: Fluctuations in the short term for electrode measurements are generally higher than those for measurements without vibration sources in the environment.

2. Hypothesis: The fluctuation comes from disturbance sources such as the ground and air flow vibration near the electrode sheet.

Experiment: With the rollers off, in an environment of no disturbance, no wind, and constant temperature, measure the thickness of the white calibration block at 4000 Hz for 20 s, calculate the range, standard deviation and repeat for three times. Then with other conditions unchanged, measure the thickness of the same calibration block while generating vibration on the system by blow air flows to it. Calculate the range, standard deviation and repeat them three times.

Result: Measurements of the calibration block have more significant fluctuations when there is a wind blowing. Vibration from the environment will increase the fluctuation range.

Observation: The measured thickness shifts in long terms when the air coming from the external environment flows through the electrode sheet.

3. Hypothesis: Shift of room temperature (which usually has a time constant of the order of 10min) causes the long-term shift in measured thickness.

   Experiment: In an environment of no disturbance, no wind, and constant temperature, and with the rollers switched off, measure the thickness of the white calibration block at 1000 Hz for 60 s, calculate the range, standard deviation and repeat for three times. Then, turn on the air conditioner (which constantly cools the temperature), measure the thickness with all other conditions unchanged, calculate the range, standard deviation, and repeat three times.

   Result: Fluctuation ranges increase after turning on the air conditioner. Temperature affects the fluctuation of measured data.

4. Hypothesis: Different times of exposure of the sensors affect the fluctuation in measured thickness.

Experiment: In an environment of no disturbance, no wind, and constant temperature, and with the rollers off, set the time of exposure to 0.12 s and measure the thickness of electrode sheet at 2000 Hz for 20 s, calculate the range, standard deviation and repeat for three times. Then, set the exposure time to 0.09 s and repeat three times with other conditions. Moreover, set the exposure time to 0.06 s and repeat three times with the same conditions.

Result: The trend of change of fluctuation range with a time of exposure is likely stochastic. Time of exposure does not affect fluctuation very much.

These explorative experiments indicate that in actual factory conditions, the environment vibration and temperature should be kept constant or at the lowest level to minimize the fluctuation in measured data. The detailed results can be found in Appendix.

Finally, we attached the electrode sheet to the rollers that simulated the working condition of the coating line in the factory and tried to find the periodic pattern as the sensors scan through the electrode sheet. The periodic pattern indicates that the thickness measuring system can detect flaws on the electrode sheet. As required by CIML, we also conducted the following two experiments to determine if periodic patterns of measured thickness can be detected while the sensors scan through different directions.

1. Move the C-shaped frame along the lead screw back and forth with a static electrode sheet. This operation scans in the direction that is perpendicular to the moving direction of the coating line.
2. Keep the C-shaped frame still with the rollers on. This operation scans the electrode sheet in the moving direction of the coating line. Since the electrode

sheet in this prototype is fixed end-to-end, we expect a periodic pattern.

These two experiments show a clear periodic pattern, proving that this prototype is viable in actual working conditions in factories. More details of the experiments can be found in Appendix.

Chapter 6. Engineering Changes Notice

This chapter will discuss the changes we have made after the final design we have made in Design Review #3 and the actual prototype. Generally speaking, we have made no change to the mainframe of our system because our design has already been carefully proofread by engineers from CIML and modified by ourselves for several iterations by the time of Design Review #3. Thanks to the precise CAD model and the carefulness of all critical dimensions, there is no interference or misfunction for the hardware parts during the assembling process. Also, for the software part, since we have separated the functions into modules, we can code and test the functionality of each component step by step. The architecture and workflow of the software are clarified and inspected to get rid of fatal faults in advance. Therefore, we do not need to make changes to our actual prototype for both hardware and software parts compared to the final design mentioned in Design Review #3.

Chapter 7. Discussion

In this chapter, a complete critique and discussion of the project are provided regarding the sensors, hardware design, and software design.

In terms of usage of the sensors and the sensing system, the resolution is high enough to accurately measure the thickness and aid quality control of the coating process in battery manufacturing. The total cost, the central part of the sensors, is less than 100,000 RMB. The sensors also passed the measurement system assessment. All essential customer requirements concerning the sensors are met in this project.

There are also some potential problems in the current prototype of the thickness measuring device, which may cause further problems in industrial applications.

1. Possible problem: A relatively fast shift in sensor reading right after starting the confocal displacement sensor system. This shift nullifies the calibration and ruins the accuracy of measurement.

   Proposed solution: Execute a “warming-up” process before measurements, i.e., turn on the system for half or one hour before calibration and measurements.

2. Possible problem: There are ovens on the coating lines in the battery factories, close to the thickness measuring system. The temperature variation during measurement can result in the thermal shift of the measured data.

   Proposed solution: Control the environment temperature near the thickness measuring system. For the initial startup, do not calibrate and start measurement until the “warm-up” process is finished and the environment temperature stabilizes.

In the validation plan explorative experiment 3, the turbulent relationship between temperature and measured thickness is validated. However, in factory applications, it is better to have a numerical correlation between them, i.e., for some point on a fixed electrode sheet, the measured thickness D should obey a specific correlation $D = f(T)$, where T is the environment temperature. With this correlation, the influence of temperature on the measured data can be compensated. Therefore, the 4th potential problem is as follows.

3. Potential problem: the correlation between temperature T and measured thickness D of an object with fixed thickness is unknown, resulting in the incapability of compensating temperature's influence.
   Proposed solution: Conduct experiments to collect a large amount of data of different measured thicknesses D and temperatures T. Label the data in column vectors $\overline{D}$ and $\overline{T}$. Then set up a few different models, such as regression, machine learning, or even deep learning if the data is plenty enough, to find out the model with the best performance in predicting D using T.

In terms of hardware design, the overall structure is robust enough to prevent most vibrations, and the size is also constrained within the size limit of 1.5 m × 1 m × 2 m.

4. Possible problem: The distance between the two beams of the C-shaped frame can be made too narrow to let the electrode sheet pass through without abrasion with the beams.

   Proposed solution: Increase the dimension between the two beams of the C-shaped frame, which gives more tolerance in manufacturing. To recover this issue facing the deadlines ahead, we can apply machining methods to slightly bend the upper beam of the C-shaped frame upward, which can largely resolve this issue.

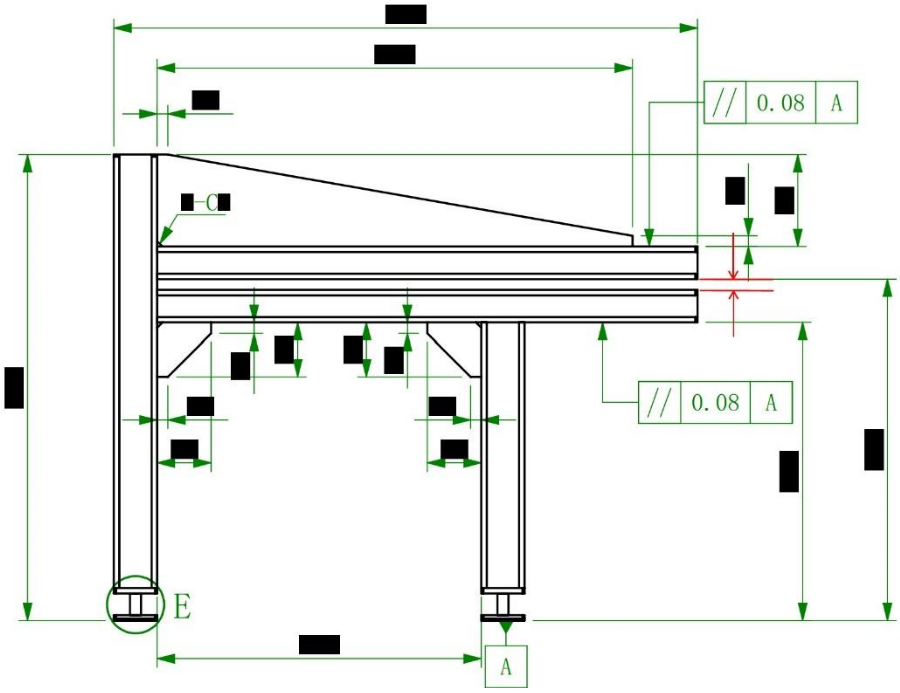


ILLUSTRATION 7.1 Proposed Solution to Potential Problem 3: Increase the Dimension Illustrated in Red

5. Possible problem: Since the range of the confocal displacement sensor is tiny (about 0.4 mm), the position of the sensors should be exact to guarantee that the moving electrode sheet always stays in the range of the sensors. Otherwise, some of the out-of-range data might be lost, and the thickness measurement for these points will fail.

   Proposed solution: Refer to the technical brochure of the confocal displacement sensors and choose the type and model of the sensor carefully to ensure that the range of detection is extensive enough for the measuring purpose. Also, try to tighten the electrode sheet as much as possible to eliminate the fluctuation caused by movement and, therefore, always be available for thickness measurements.

6. Possible problem: After the sensors are installed on the C-shaped frame and adjusted to become co-axial, it requires some standard blocks in between for calibration procedure. However, there is no platform for us to hold the standard blocks and do the calibration.

   Proposed solution: Use metalworking skills or additive manufacturing technologies to design and manufacture a holding platform that can be temporarily mounted to the C-shaped frame for calibration usage.

In terms of software design, we have implemented a C# software to fetch data from the sensor system and interact with users. The strengths are listed below:

1. The software almost implements all the necessary features required, including user guide, connection to the sensor system, calibration, two ways to take measurements, data export, data filtering, and data visualization. We are proud that our software is a complete system that can interact directly with the sensor system.

2. The software provides other extensive features to improve user experience, including a modern user interface, light/dark color themes, progress bars, login time display, and instant feedback via prompts. These small features can help users better understand the underlying processes and quickly find the correct to use our software.

3. The software is implemented in visual studio using C#. It is a typical programming environment, particularly for industrial software. Additionally, it is also what our sponsor used within the company, which means it will be easy for them or anyone interested to adjust secondary development work on top of our software.

Nevertheless, there are still some potential problems. Looking back now, we do not doubt that some weaknesses could have been avoided at the beginning of this project. Furthermore, we hope these lessons are helpful for anyone interested in our project.

1. Possible problem: The software and hardware timestamps are not consistent. It takes time from function calls to the sensor system's receiving signals. It also takes time from the sensor system's receiving signals to its starting measurements. Based on our experience, the start-up time due to the above two reasons can be 0.1 to 0.3 seconds, non-deterministically, which could significantly influence the performance of a high-precision system like ours. Therefore, it is a bad idea to regard computer system time as the actual time of the measurements. However, after consulting Shenzhen LightE technology company, we know they never thought about this need before, and there is no way to get hardware timestamps.

   Proposed Solution: This problem is mainly caused by the weakness of the sensor system selected. The trivial solution is to request the sensor company to implement this feature in their sensor system or keep it in mind when selecting sensors. Nevertheless, there may be currently no such product, particularly given the budget constraint in this project. In this case, an alternative way is to extend the measuring time and approximate sampling frequency. After doing some testing, we found that the sampling frequency of the sensor system is relatively accurate after the sensor start-up time. Besides, there is a function in LightE SDK that enables us to get the number of points measured so far. Therefore, it is possible to spawn a thread continuously recording the number of measurements and corresponding system time. Moreover, we can assume the measurements that happen in-between are of the same time gaps.

2. Possible problem: Currently, we allocate a local double array of fixed sizes to store all the measurements recorded. Furthermore, this local variable will not be freed unless the program terminates. This method works well if the number of measurements is not big, for example, 50 Hz for five minutes. However, if the number of measurements is too big, the size can easily exceed the stack size in C#, which is 1 MB for 32-bit and 4 MB for 64-bit processes. For example, 50 Hz for 30 minutes means, 2 doubles * 8 Byte/double * 50 * 60 * 30 = 1.37 MB, which challenges the C# stack size.

   Proposed Solution: This problem is hard to solve. Given that the product line does not often stop in the factory, our measuring system continuously takes measurements. However, we need to free our space regularly, which means storing the measurement data in other places regularly. We can create a MySQL database. Every ten minutes, the local data can be exported into the database while our sensor moves from one electrode sheet to the other, that is, the time that does not require measurements. After the sensor stops moving, the local array should be freed and re-allocated and start successive measurements. In this way, space can be freed without losing any data or missing any measurements.

Chapter 8. Conclusion

In this project sponsored by CIML, we build a prototype of the non-contact thickness measuring device for coating process in battery manufacturing, after a thorough investigation of different thickness measuring principles and matured solutions, a careful design process of hardware and software with considerations to the established customer requirements, and a series of validation experiments.

First, we summarize the design problem as follows:

1. Real-time, continuous thickness measurement of the electrode sheet is the most critical characteristic of coating quality. The current thickness measuring device embedded in the actual production line can only monitor the coating thickness after it has been dried. Additionally, imported from overseas, the current thickness measuring device is expensive and large. Therefore, a novel measuring device used before the drying process with a small and low cost is needed.
2. Among current coating thickness measurement methods in practice, ultrasonic and confocal displacement methods are consistent with our customer requirements. After comparing three state-of-the-art industrial products in terms of Range/Frequency/Resolution/Linearity/Cost/Spot Diameter, LightE D35 outperforms the other two products.
3. The result of QFD in Chapter 2 shows that cost, sampling frequency, accuracy, and resolution are the four most essential specifications during our design process. For the correlation between engineering specifications, while cost is almost negatively correlated with every other specification, the remaining engineering specifications are positively correlated.

The outcomes of this project are summarized as follows:

1. The selected design is a mechatronic system containing a hardware subsystem and a software subsystem. The hardware is the C-shaped frame and support structures and the sensors, which can scan through the width of the coating line. The software subsystem is a graphical user interface that acquires, filters, visualizes, and transmits the measured data from the sensor.
2. Validation experiments for two engineering specifications, resolution and stability, are carefully designed and conducted, promisingly validating the selected design.
3. Further potential problems are brainstormed, and solutions to them are also proposed. Although these concerns are inconspicuous for the current stage of the prototype, they are vital in the success of measurement in factory applications.

The quality of the solution is validated through a series of experiments, which measure the design’s accuracy, stability, and reliability.

Chapter 9. Project Plan and Future Works

9.1 Major Milestones

1. Selection of sensors. We finished the process of literature survey and evaluation of engineering specifications shortly after the design review.
2. Test of the software development kit. We must be familiar with the SDK provided by manufacturers to develop the software further. The test was finished before the end of July.
3. Design of the prototype. The hardware is the project's backbone, and the quality of the design directly affects the result. The prototype is divided into the moving C-shaped frame and testbed, both designed concurrently and finished before August.
4. Manufacturing. As the design of our hardware is quite complicated, the manufacturing took much time. Till now, most of the components have been finished and delivered to us. However, some important ones, such as roller sets, are still under manufacturing and will be delivered next week. It might hinder us from fully validating the product. Luckily, we have a complete makeshift plan for nearly every component. While the manufacturing will be finalized before the end of August, we have been halfway through all validation plans.
5. Validation of the prototype. Thorough experiments are needed to validate whether the prototype passes all pre-set engineering specifications. If not, it helps to pinpoint the problem of the prototype and prepares the sponsor or us for further improvement. Due to the delay in the manufacturing process, we have not finished all experiments, but they will be finished before the final delivery.

6. Coupling of hardware and software. While the software and mechanical design are relatively independent initially, it is vital to ensure that all components can work together at some point. Again, due to practical constraints of manufacturing, we are still working on this issue and hopefully will finish it before the end of August.
7. Technical communications. It comprises oral presentations and written reports for design reviews. Expo is the last milestone for the project.

TABLE 9.1 summarizes all milestones and their current status.

TABLE 9.1 Summary of Milestones

Milestones	Status (plan if not finished)
Selection of sensors	Finished
Test of the software development kit	Finished
Design of the prototype	Finished
Manufacturing	Finished
Validation of the prototype	Finished
Coupling of hardware and software.	Finished
Technical communications	Finished

9.2 Gantt Chart

As shown in ILLUSTRATION 9.1, the project is divided into four stages, and technical communications are singled out. We have finished all pre-set goals before the EXPO. The major milestones have been explained in the last section.

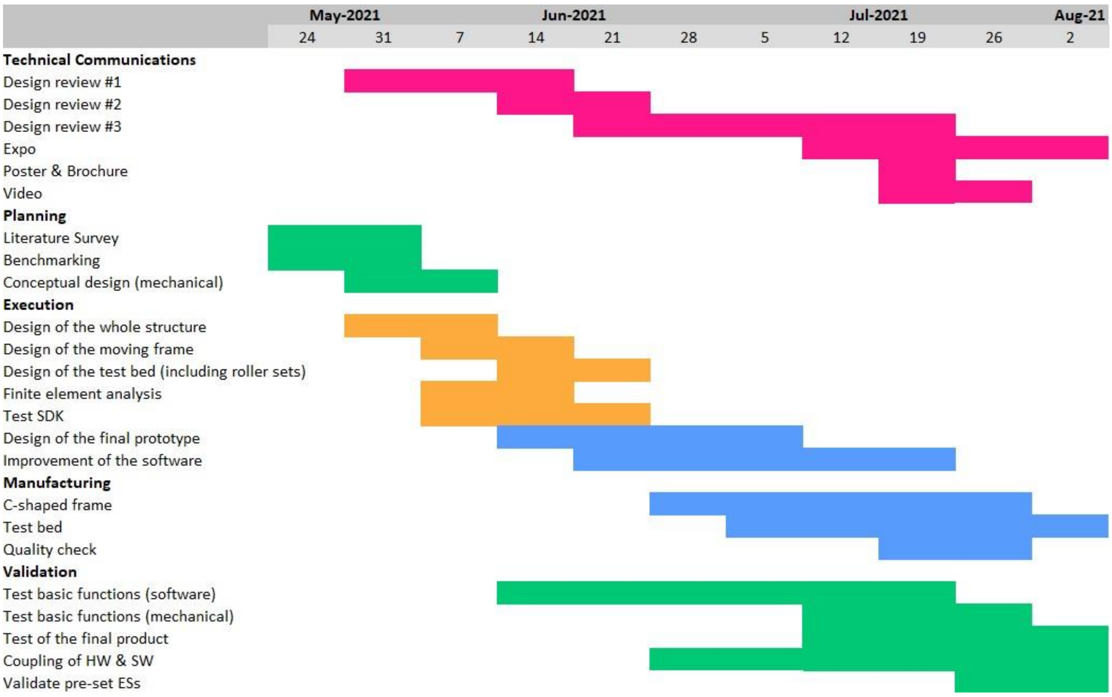


ILLUSTRATION 9.1 Gantt Chart

9.3 Work Load

As summarized in TABLE 9.2, each member is expected to devote 20 hours to the project per week. The workload is distributed evenly.

TABLE 9.2 Work Load Distribution

Name	Main tasks	Hours/week
Jiajin Wu	Mechanical design & test	15
Zefang Li	Mechanical design & test	15
Zhiyang Chen	Software design & test	15
Yuenong Ling	Finite element analysis & Mechanical test	15
All	Technical communications	5

9.4 Future Works

What to do with this project in the future is to test the thickness measuring system on the coating lines in battery factories. The hardware system should be embedded into the coating line hardware system, the factory engineers and workers should test the software system, and the sensor we are using should be tested in a factory environment with varying temperatures. There are three aspects of future works under the system-level improvements and tests: hardware design, assembly, and user interface functions.

For hardware design, we would like to modify the design of the C-shaped frame. The current design of the gap between two beams is too narrow for the electrode sheets to pass through, which is not reliable enough for the actual product line. Also, the stability of the C-shaped frame to support and fix sensors could be refined. For the movement module, the current solution of the servo motor and guide screw can also be improved to eliminate the residual vibrations.

For assembly, tolerances of the C-shaped frame can be further improved, especially for the parallelism between the two beams, which affects the two sensors when they are assembled. The diameter of the holes on the baseboard for foot cups should also be shrunk from 17.5 mm to 16.5 mm to improve the system's stability after assembly.

For hardware/software timestamps consistency, as mentioned in Chapter 7, our current solution approximates hardware timestamps using software system time and a few assumptions based on our experience. Very likely, this approximation does not satisfy the testing engineers in the factory. Thus, we must find ways to acquire hardware timestamps, either by requesting help from the sensor company or switching to another sensor brand.

For data storage, the current spreadsheet-like method works well for a relatively small amount of measurement data. Nevertheless, a modern database like SQL should be developed if the software will be integrated into the comprehensive industrial measuring system. SQL can be faster, safer, and easier to share among different applications.

Our current prototype works well for calibration since it only gets thickness data from the sensor system and system time from computers. In the future, when integrating our system into an existing product line, probably our measuring system also needs to get real-time data from product line roller encoders, screw motors, and other devices. How to synchronize that different quantities can be critical to the precision of this system. Therefore, a set of calibration methods should be designed to synchronize these quantities with each other.

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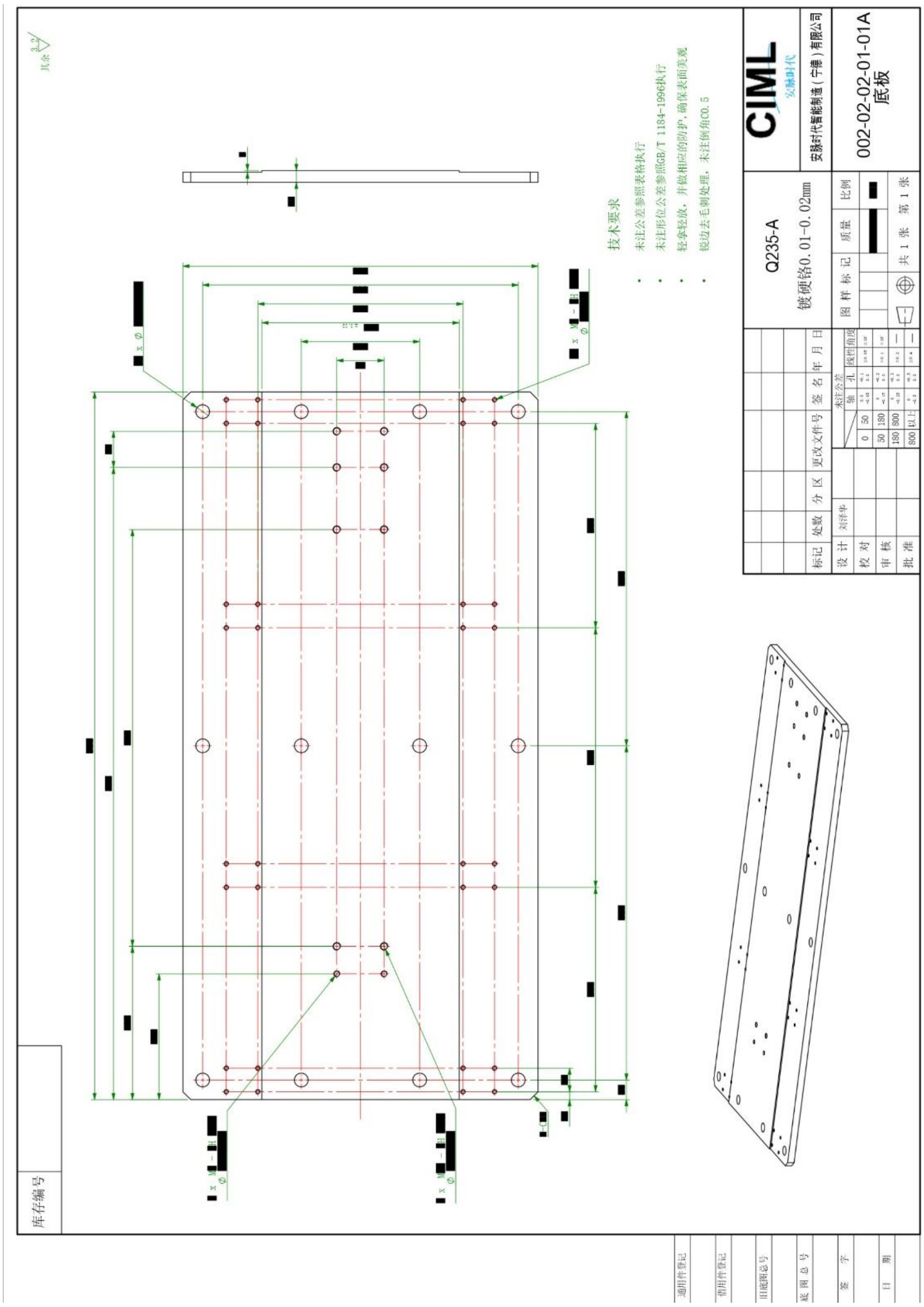
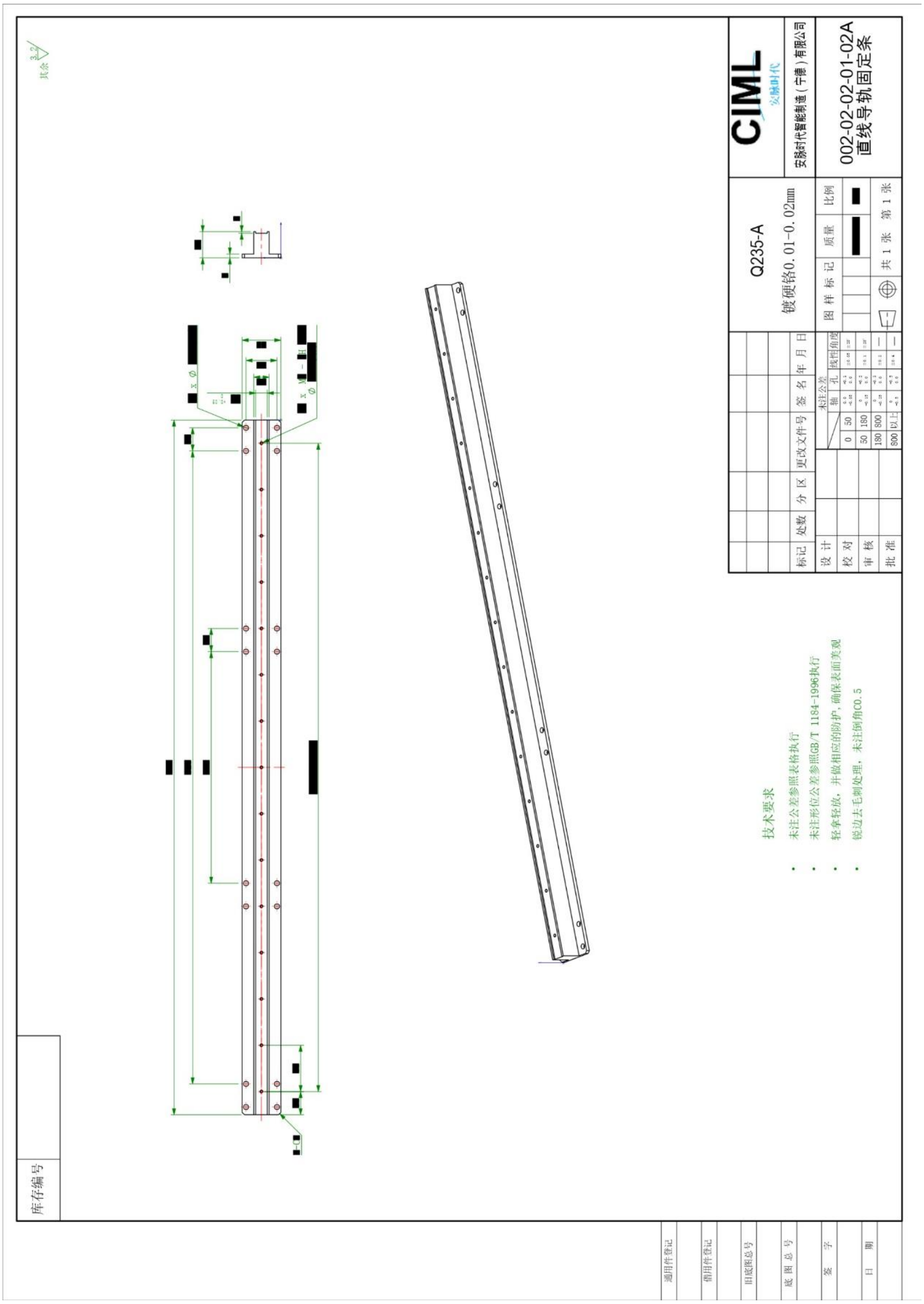
Appendix

Appendix I. Engineering drawings

The engineering drawings with confidential dimensions concealed are listed below.

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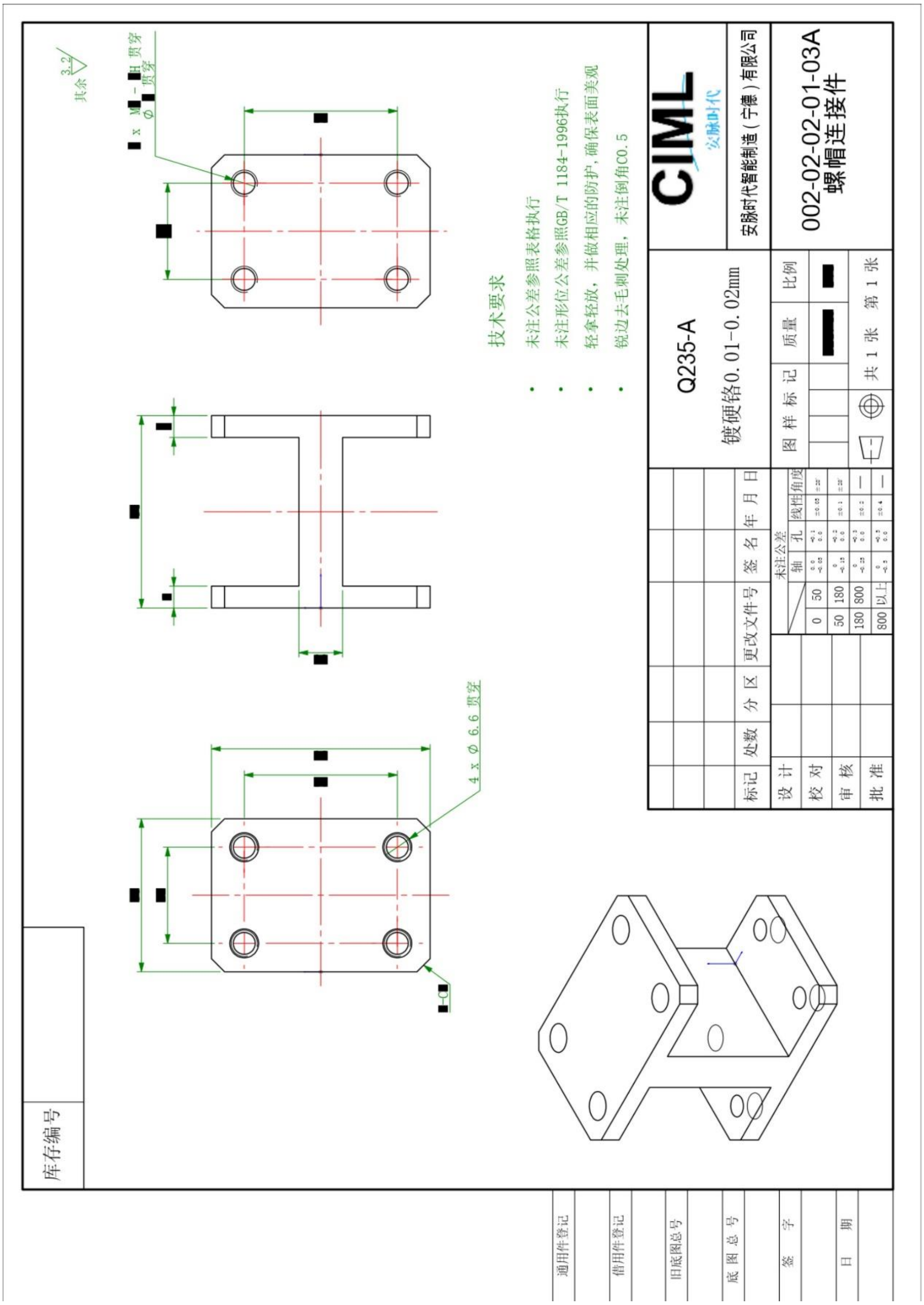
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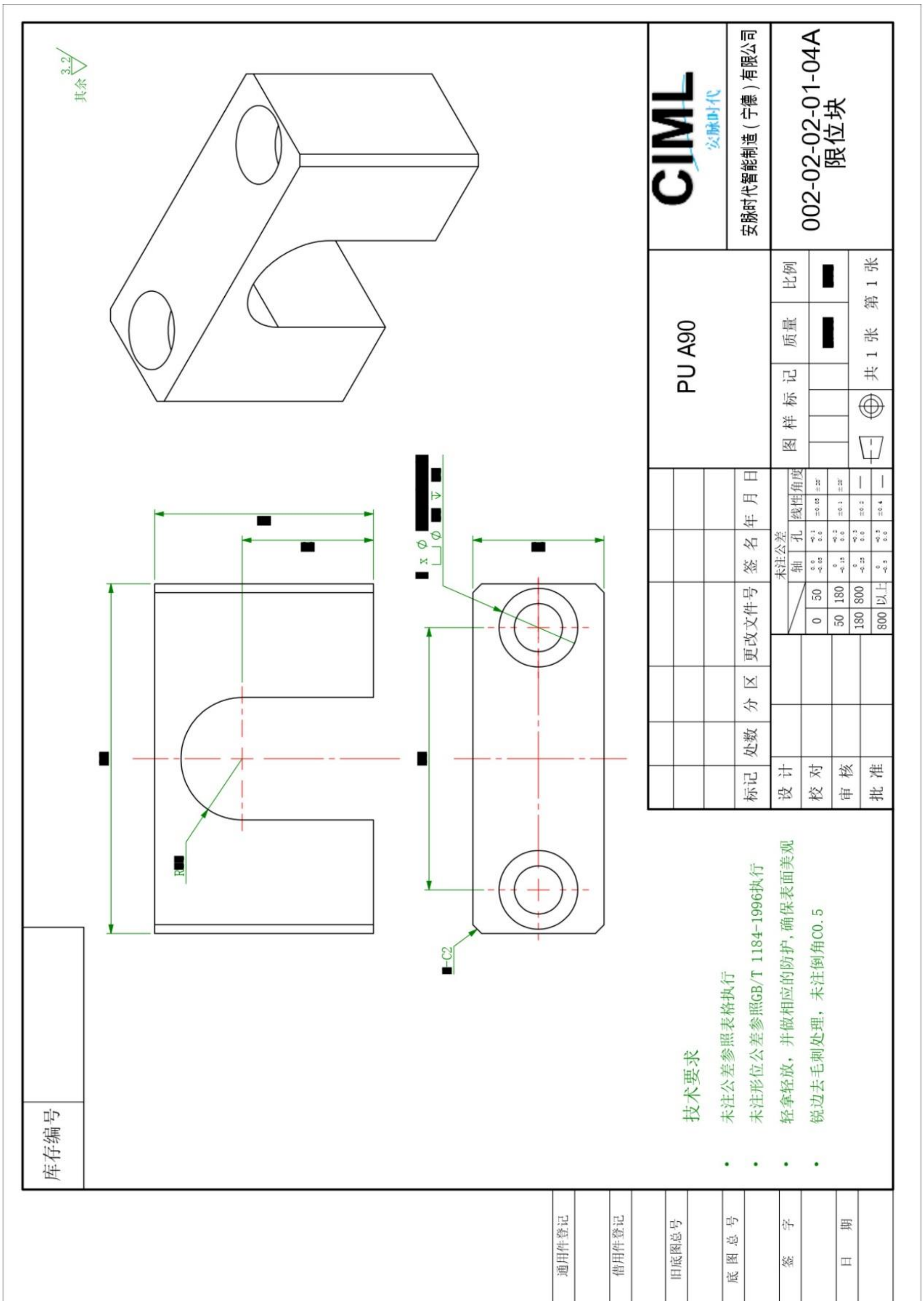
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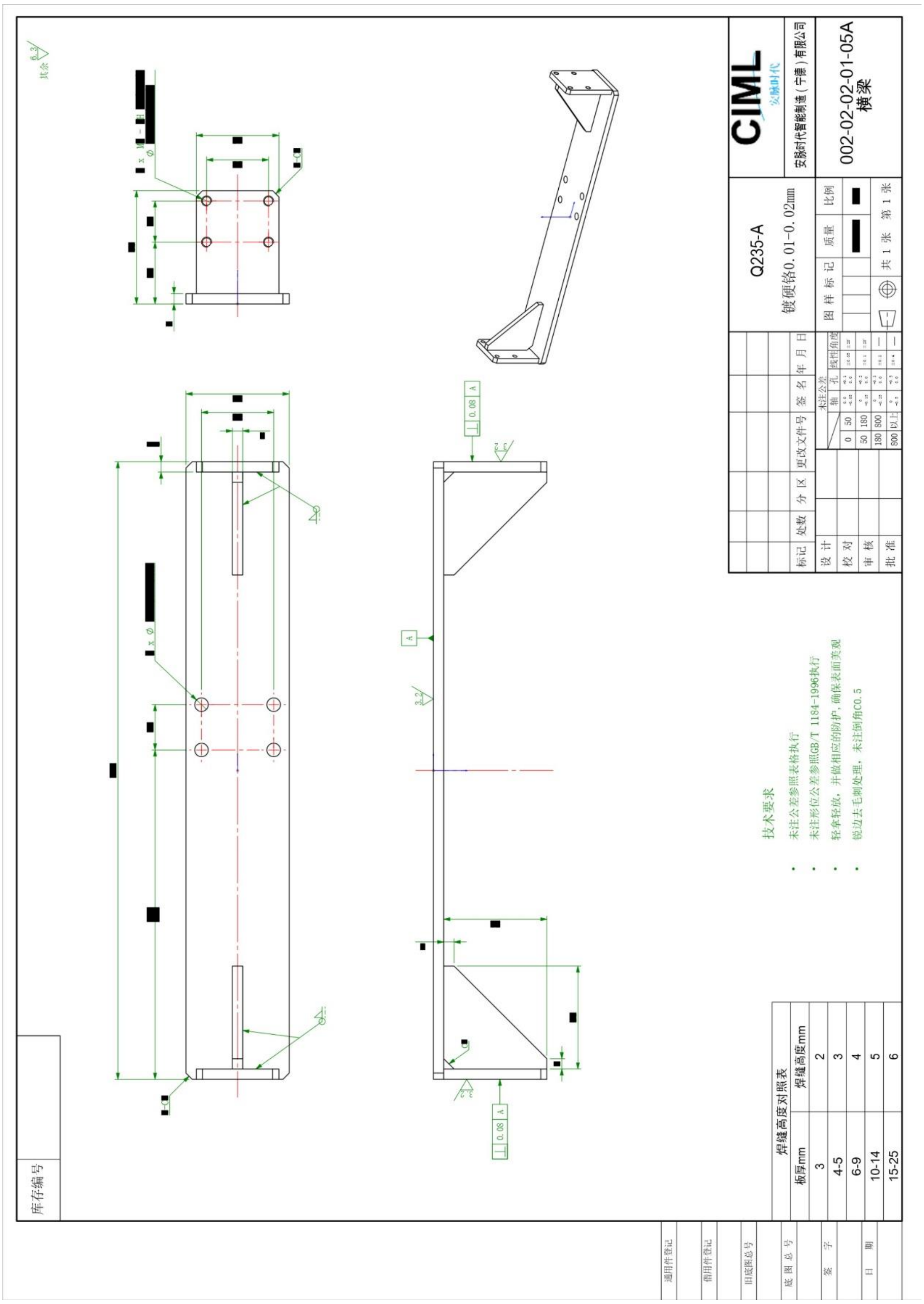
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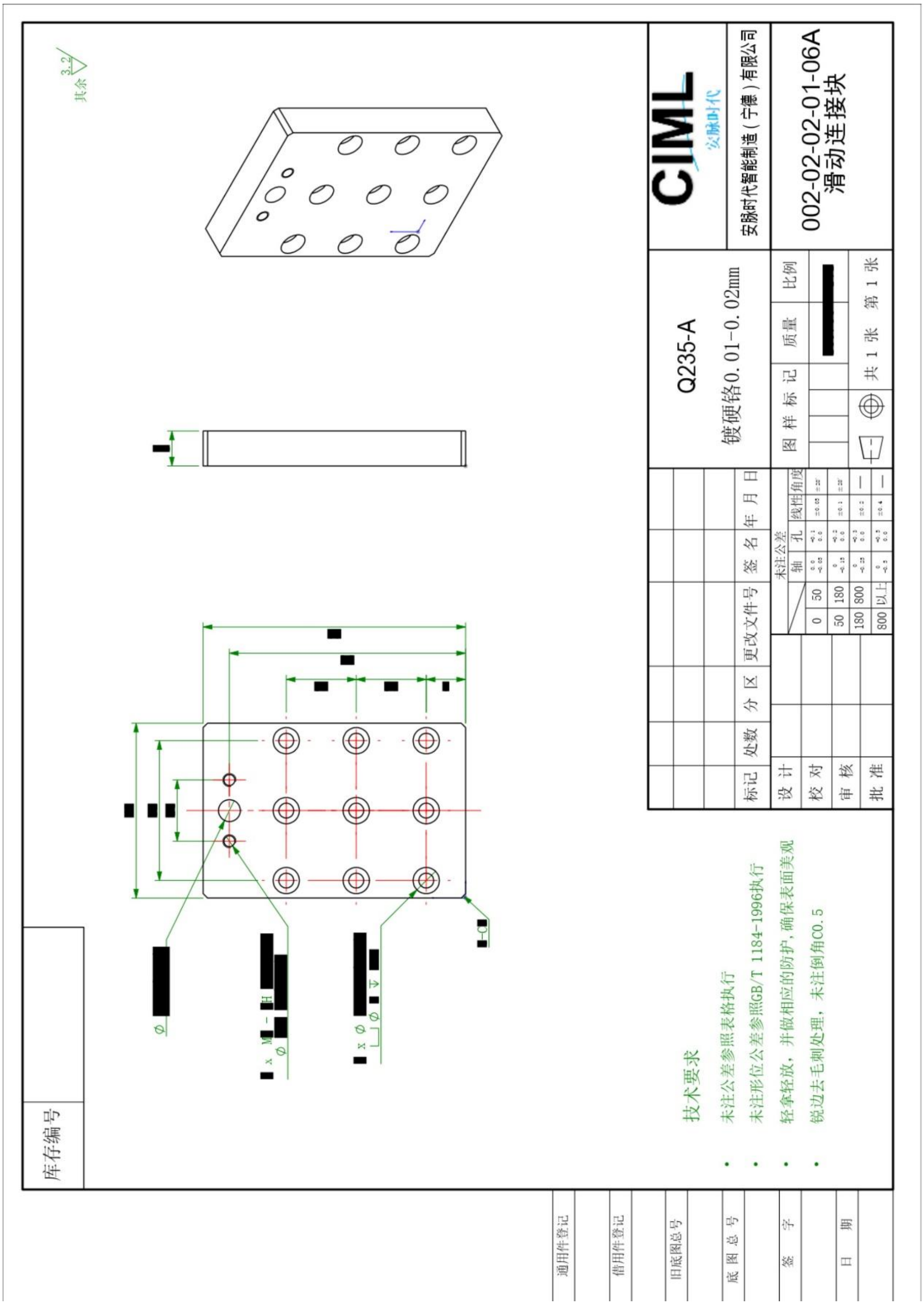

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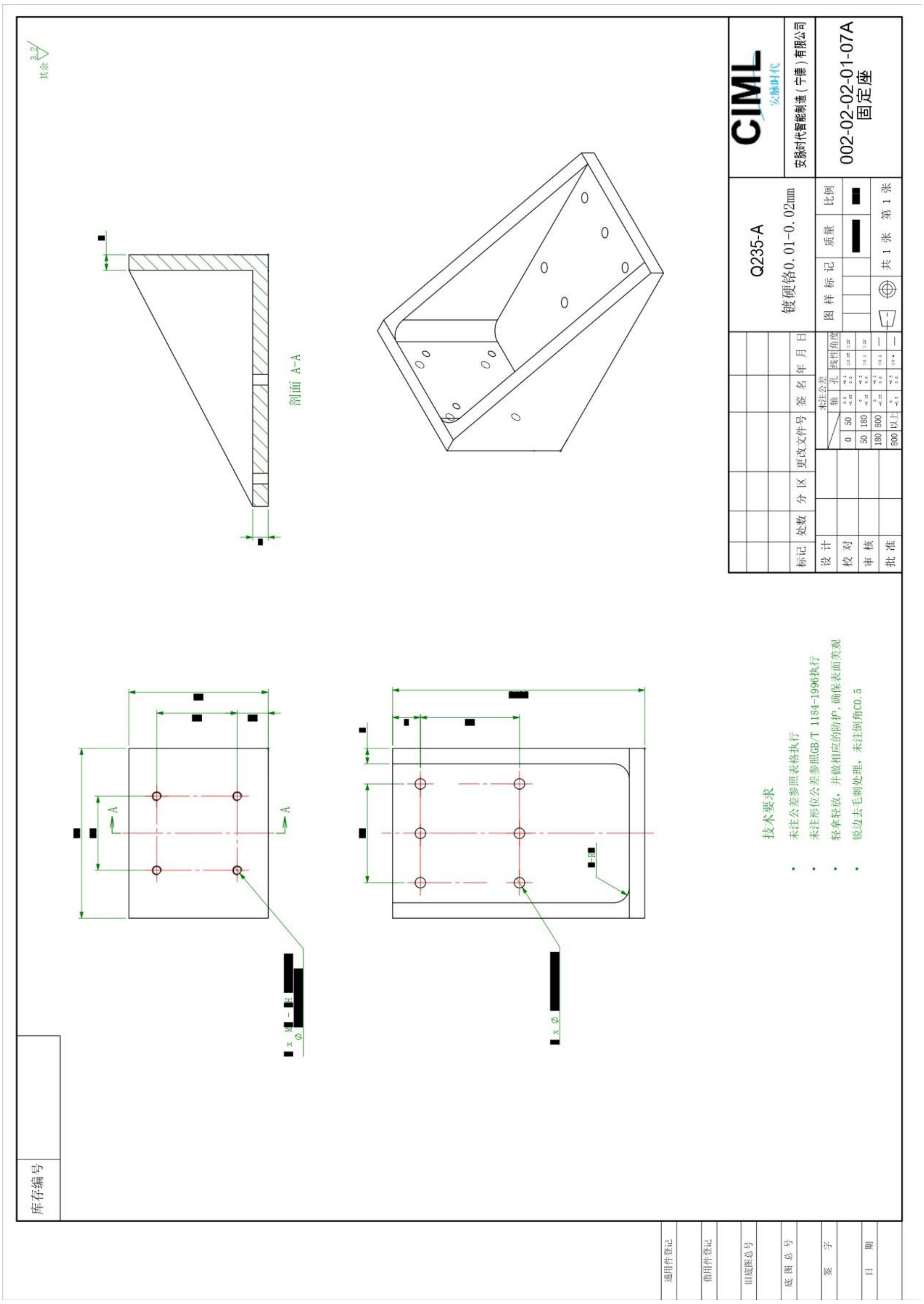
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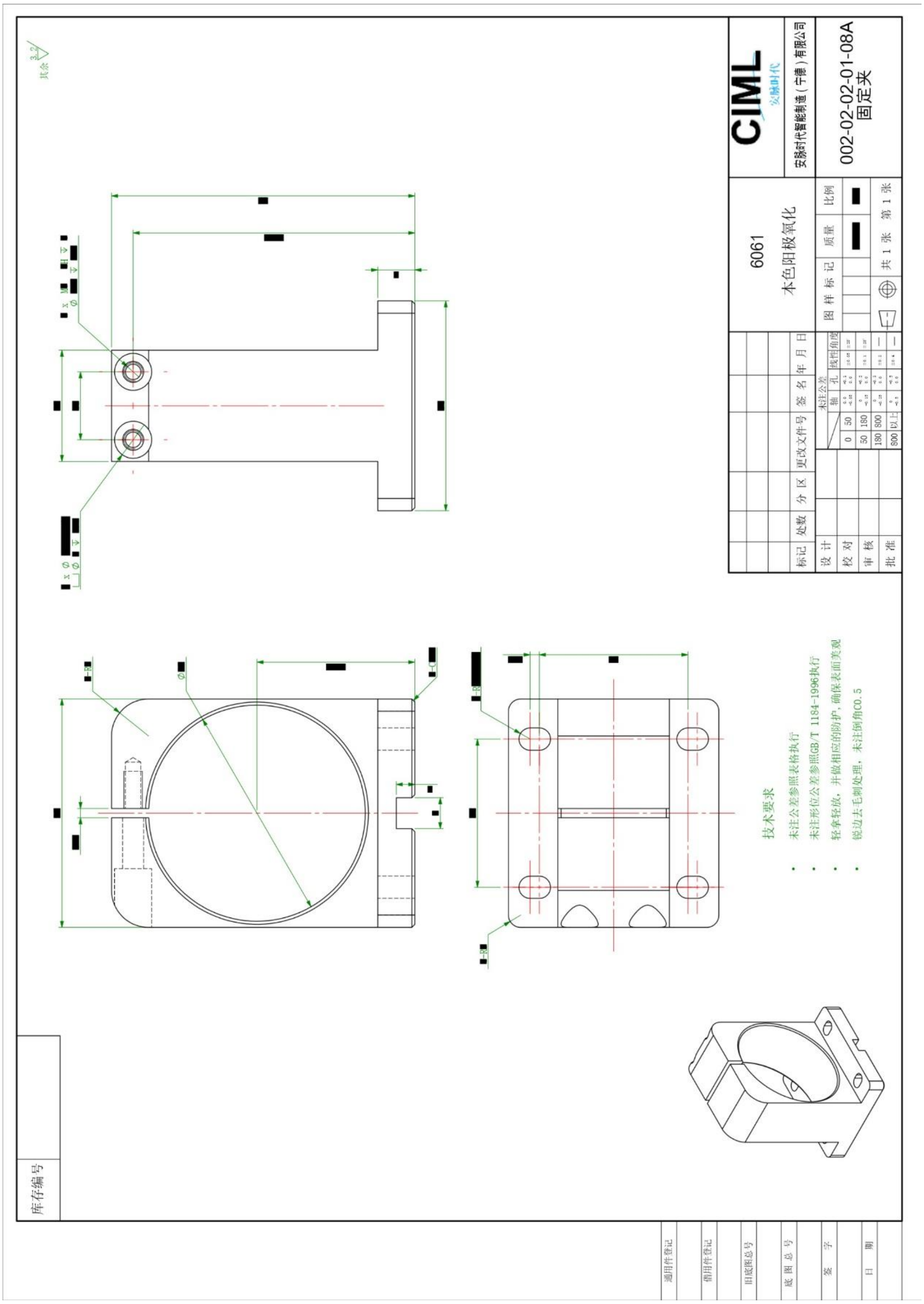
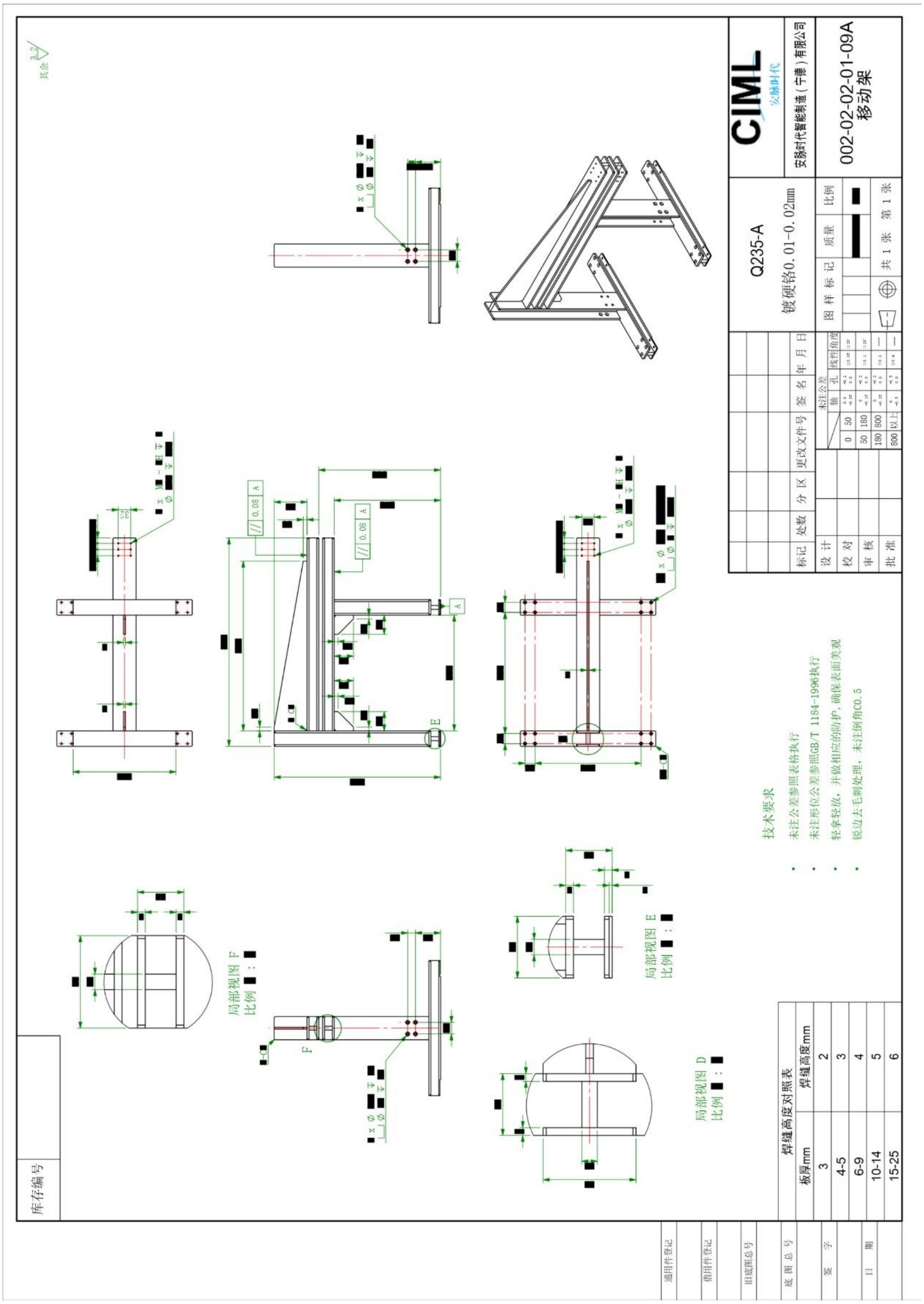

CIML
安脉时代智能制造（宁德）有限公司
002-02-02-01-08A
固定夹
6061
本色阳极氧化
技术要求
未注公差参照表格执行
未注形位公差参照GB/T 1184-1996执行
轻拿轻放，并做相应的防护，确保表面美观
锐边去毛刺处理，未注倒角C0.5
库存编号


CIML
安脉时代智能制造（宁德）有限公司
002-02-02-01-09A
移动架
Q235-A
镀硬铬0.01-0.02mm
技术要求
未注公差参照表格执行
未注形位公差参照GB/T 1184-1996执行
轻拿轻放，并做相应的防护，确保表面美观
锐边去毛刺处理，未注倒角C0.5
焊缝高度对照表
板厚mm 焊缝高度mm
3 2
4-5 3
6-9 4
10-14 5
15-25 6
局部视图 D
局部视图 E
局部视图 F
库存编号

Appendix II. Bill of Materials

The bill of materials is listed below in support of the fabrication process.

TABLE APPENDIX II.1 Bill of Materials

Item	Quantity	Source	Catalog Number	Cost (RMB)	Contact	Notes
base board	1	CIML	Non-standard	-	-	
C-shaped frame	1	CIML	Non-standard	-	-	
coupling	1	yhda	DEG51-D33-d10-e14-DD	-	yhdfa.com	
foot cup	6	HONGLAIYUAN	D80-M16*200	62.94	shop104138234.taobao.com	
lead screw & support	1	CIML	Non-standard	-	-	
rollers	4	Jiangsu Winroller Techonology	DGBL76-100W-B-24V-18M-500L-S3 JZ86-I-H3-H4	1500	shop72576425.taobao.com	
roller support	8	诚信传动	UCTFU204B	376	szskfzc.taobao.com	
roller support frame	4	CIML	Non-standard	-	-	
Servo motor	1	INOVANCE	MS1H1-20B30CB-A331Z	-	inovance.cn/	
Servo motor controller	1	INOVANCE	SV660N-Size A	-	inovance.cn/	
slide rail support	2	CIML	Non-standard	-	-	
slide rail	2	CIML	BSTP20	-	yhdfa.com	
sliders	4	CIML	BSTP20	-	yhdfa.com	

The non-standard parts, although designed by our team, are purchased and offered by the sponsor. Therefore, their source is CIML, and their costs are confidential. CIML also orders some standard parts, and the prices are also confidential. Therefore, we label it as “-.” Nevertheless, what we can disclose is that the total cost is less than 10,000 RMB. The assembly process also needs screws and nuts, which are not listed here as less significant.

Appendix III. Engineering Changes Notice

After Design Review #3, there is no change since the hardware has been carefully designed with engineers from CIML, and modules complete the software.

Appendix IV. Validation Experiment Details

This section presents the detailed information of Chapter 5. The subsections of this section follow the order of those experiments in Chapter 5.

Appendix IV. I Evaluative Experiments

1. The range of every measurement (no matter what the frequency is) within a short period, e.g., 1 s, is within 1 µm. A sample measurement for 1 s is plotted below, with a sampling frequency of 4000 Hz. It is clearly shown that the range is within 1.0 µm, which satisfies the customer requirements.

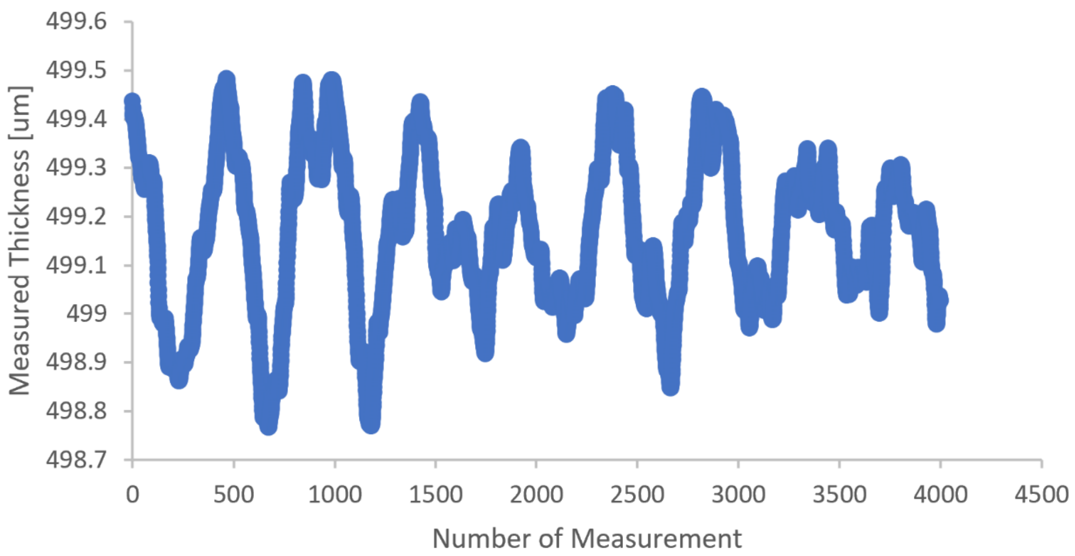


ILLUSTRATION APPENDIX IV.1 Range of Measurement

2. Measurement system assessment of the sensor system is conducted for the whole system, and the %GRR value is calculated to be 9.91%, which is less than 10%,

indicating that the reliability and reproducibility of this system are acceptable. The total result of MSA is shown below. CIML provides the calculation sheet.

评价人/		零件										平均值	
测量次数		1	2	3	4	5	6	7	8	9	10		
A	1	170.7369	164.8084	158.8633	169.0813							A_1	165.87246
	2	169.9468	164.1022	158.7248	170.0763							A_2	165.71256
	3	170.5299	165.5337	158.969	169.0988							A_3	166.03284
平均值		170.40453	164.81477	158.85236	169.41881							$\bar{X}_A$	**165.87262**
极差		0.79006	1.43145	0.24418	0.99505							$\bar{R}_A$	**0.86518**
B	1	169.5293	164.7674	158.2856	168.4746							B_1	165.26421
	2	169.5293	164.7982	158.6239	168.4888							B_2	165.36004
	3	168.372	164.4889	158.7469	169.0447							B_3	165.16313
平均值		169.14351	164.68485	158.55215	168.66933							$\bar{X}_B$	**165.26246**
极差		1.15732	0.30929	0.46129	0.57013							$\bar{R}_B$	**0.62451**
C	1	168.8754	164.1	158.7663	168.6929							C_1	165.10865
	2	169.7772	164.7424	158.4052	169.4025							C_2	165.58181
	3	169.7772	165.7476	158.2463	169.9802							C_3	165.93779
平均值		169.47657	164.86332	158.4726	169.35852							$\bar{X}_C$	**165.54275**
极差		0.90173	1.64758	0.52002	1.28727							$\bar{R}_C$	**1.08915**
零件平均值		169.6749	164.7876	158.6257	169.1489							$\bar{\bar{X}}_P$ =	165.55928
零件平均值极差												R_P =	11.04917
$\bar{\bar{R}}$ = $(R_A + R_B + R_C)$/ Appraiser = (					0.86518	+	0.62451	+	1.08915	) /	3	=	0.85962
$\bar{X}_{DIFF}$=		[Max $(\bar{X})_{ABC}$]	—	[Min $(\bar{X})_{ABC}$] =	165.87262	—	165.26246					=	0.61016
UCL_R=		$\bar{\bar{R}}$	×	*D_4 =	0.85962	×	2.575					=	2.21351
UCL_{xbar}=		$\bar{\bar{X}}p$	+	A2	×	$\bar{\bar{R}}$ =	165.559	+	1.0230	×	0.8596	=	166.43866
LCL_{Xbar}=		$\bar{\bar{X}}p$	—	A2	×	$\bar{\bar{R}}$ =	165.559	—	1.0230	×	0.8596	=	164.67989

测量单元分析			**总变差%（TV）——基于零件变差**	
重复性—设备变差（**EV**）				
EV = $\bar{\bar{R}} * K_1$			% EV =	100[EV/TV]
= 0.50786	**Trial#**	**K_1**	=	8.74%
	3	0.5908		
再现性—评价人变差（**AV**）				
AV= $\sqrt{(\bar{X}_{DIFF} * K_2)^2 - (EV^2 / (nr))}$			% AV =	100[AV/TV]
= 0.27058	**Appraiser**	**K_2**	=	4.66%
（n =Parts，r =Trials）	3	0.5231		
重复性和再现性（**GRR**）				
GRR= $\sqrt{(EV^2 + AV^2)}$			**% GRR =**	**100[GRR/TV]**
= 0.57544			**=**	**9.91%**
零件变差（**PV**）				
PV= $R_P * K_3$ （PV=$\sqrt{TV^2 - GRR^2}$）	**Part #**	**K_3**	% PV =	100[PV/TV]
= 5.77982	3	0.5231	=	99.51%
总变差（**TV**）			区别分类数（**ndc**）	
TV= $\sqrt{(GRR^2 + PV^2)}$ (TV= Total Tolerance/6)			ndc=	1.41*PV/GRR
= 5.808395006			=	14

ILLUSTRATION APPENDIX IV.2 MSA Data and Results

Appendix IV. II Evaluative Experiments

1. Experiment 1:

   1.1 In an environment of no disturbance, no wind, and constant temperature, and with the rollers off, measure the thickness of the white calibration block at a constant frequency (4000 Hz) for 20 s.

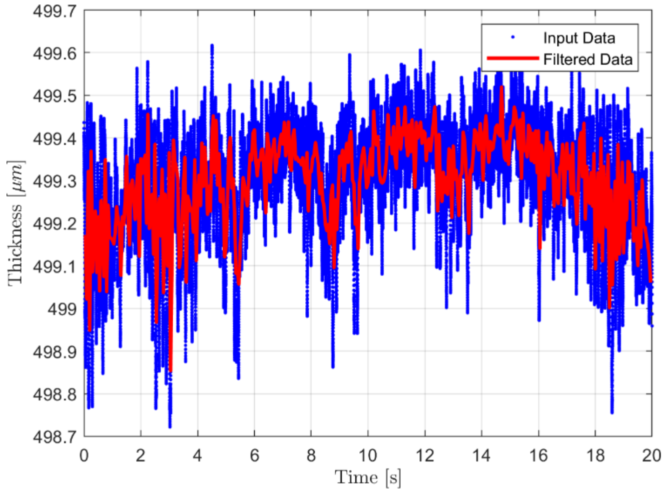


ILLUSTRATION APPENDIX IV.3 Experiment 1.1

1.2 Repeat 1.1

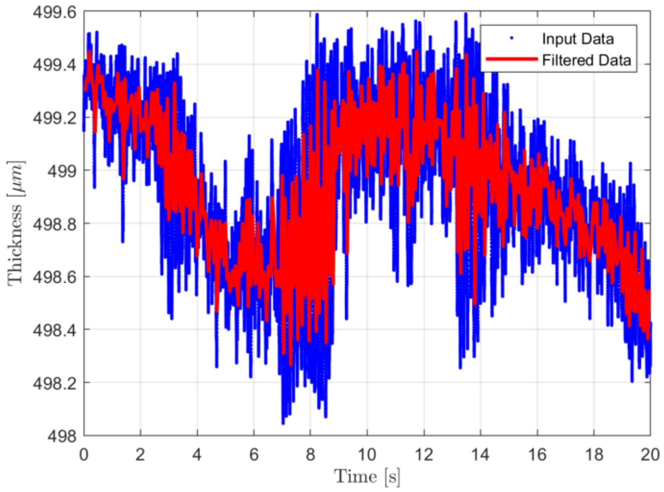


ILLUSTRATION APPENDIX IV.4 Experiment 1.2

1.3 Repeat 1.1

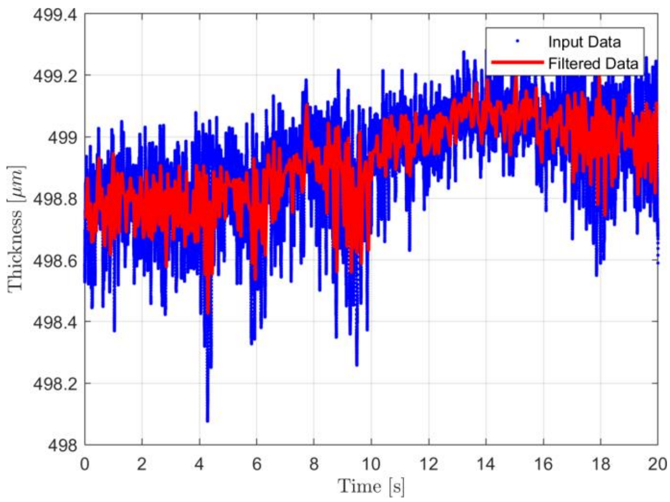


ILLUSTRATION APPENDIX IV.5 Experiment 1.3

1.4 Then in the same condition, measure the same calibration block that is the same in the previous experiment but is painted to black, at a constant frequency (4000 Hz) for 20 s, calculate the range, standard deviation, and repeat three times.

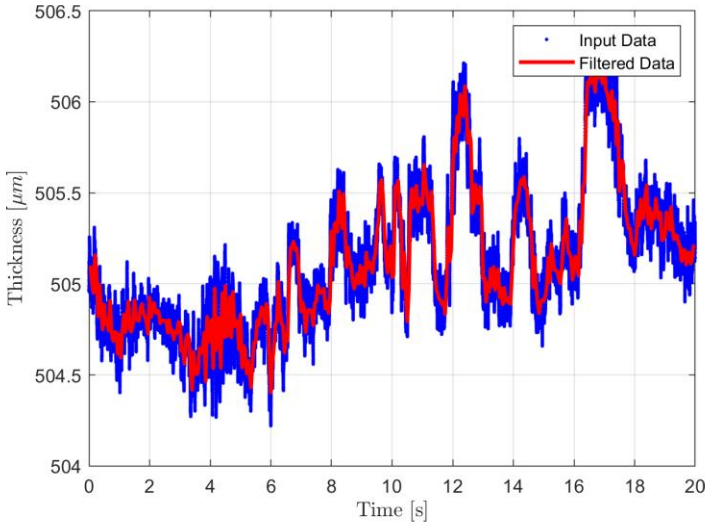


ILLUSTRATION APPENDIX IV.6 Experiment 1.4

1.5 Repeat 1.4

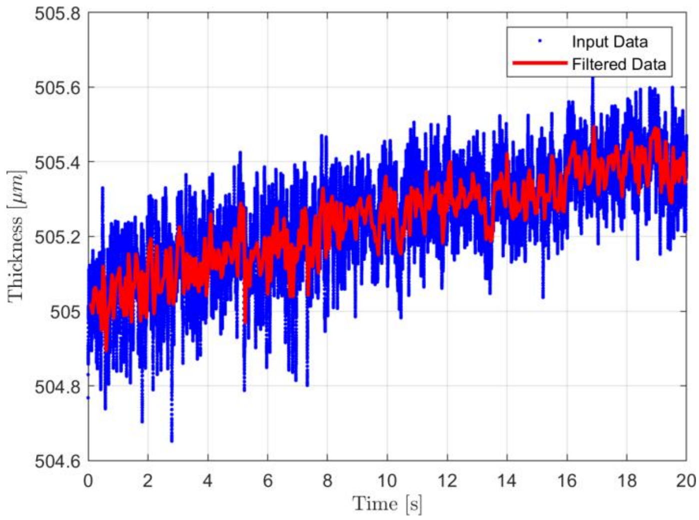


ILLUSTRATION APPENDIX IV.7 Experiment 1.5

1.6 Repeat 1.4

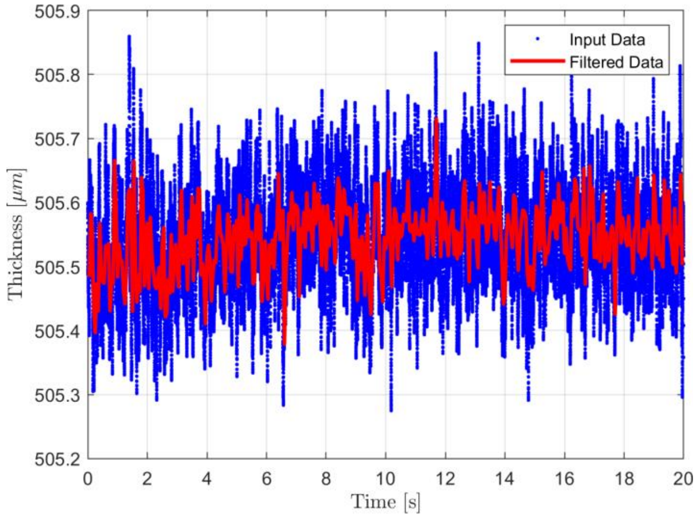


ILLUSTRATION APPENDIX IV.8 Experiment 1.6

The ranges and standard deviations are listed below.

Exp	Range_raw	Std_raw	Range_filtered	Std_filtered
1-1	0.896	0.134	0.781	0.124
1-2	2.112	0.397	1.957	0.393
1-3	1.544	0.310	1.439	0.300
1-4	1.000	0.142	0.738	0.133
1-5	1.245	0.173	1.157	0.165
1-6	0.585	0.081	0.480	0.067

TABLE APPENDIX IV.1 Experiment 1

2. Experiment 2:

2.1 With the rollers off, in an environment of no disturbance, no wind, and constant temperature, measure the thickness of the white calibration block at 4000 Hz for 20 s, calculate the range, standard deviation.

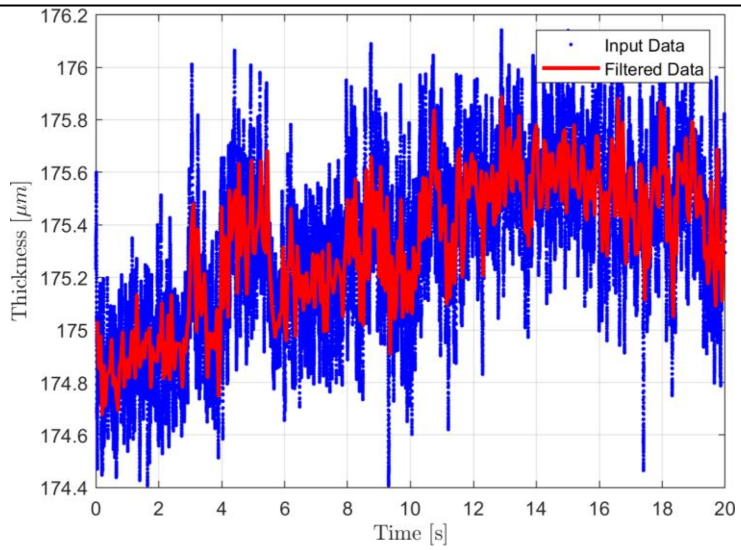


ILLUSTRATION APPENDIX IV.9 Experiment 2.1

2.2 Repeat 2.1

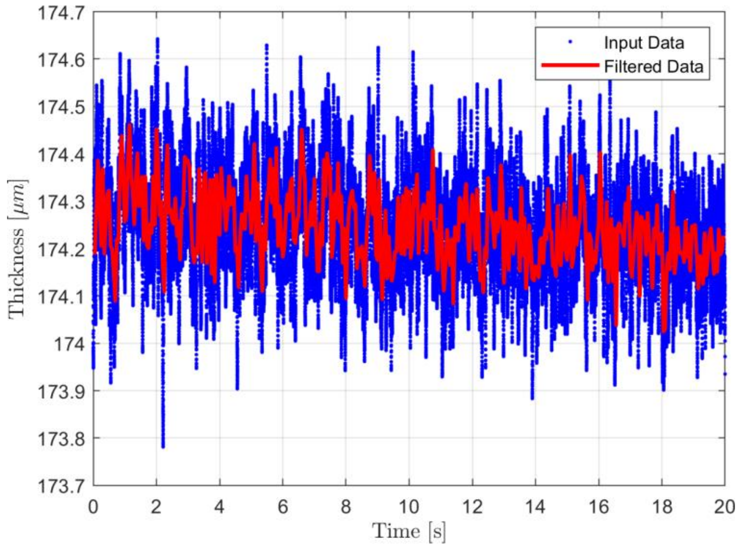


ILLUSTRATION APPENDIX IV.10 Experiment 2.2

2.3 Repeat 2.1

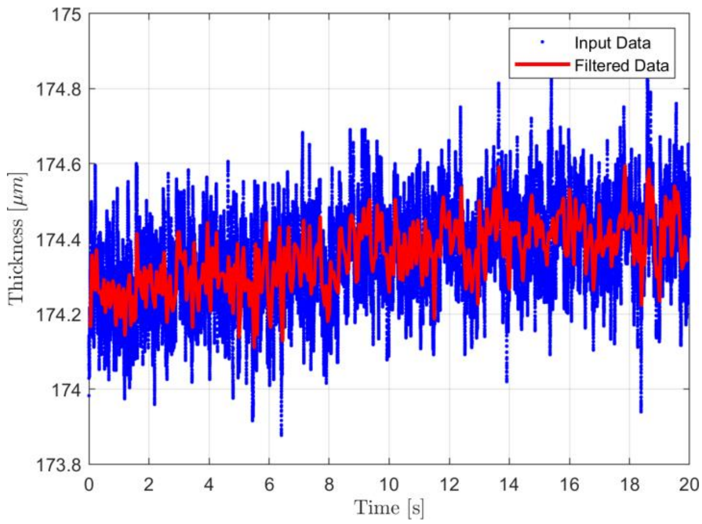


ILLUSTRATION APPENDIX IV.11 Experiment 2.3

2.4 Then with other conditions unchanged, measure the thickness of the same calibration block while generating vibration on the system by blow air flows to it. Calculate the range, standard deviation and repeat them three times.

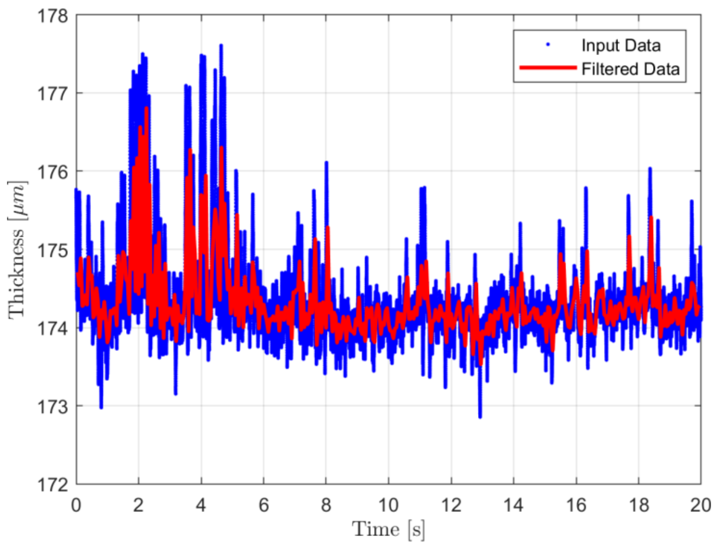


ILLUSTRATION APPENDIX IV.12 Experiment 2.4

2.5 Repeat 2.4

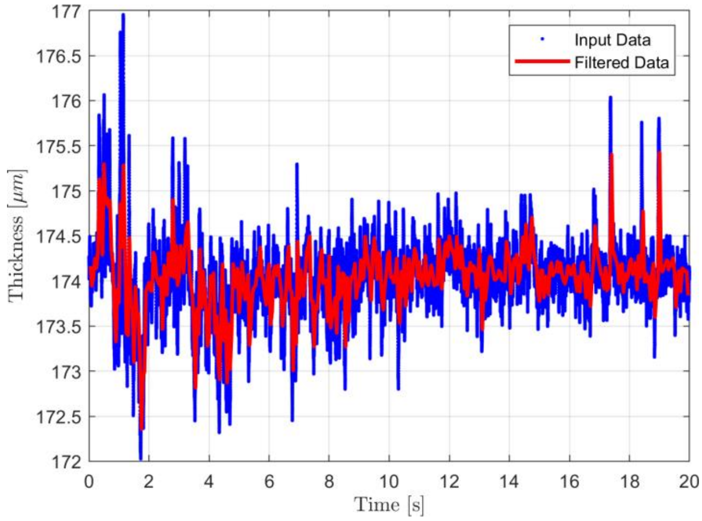


ILLUSTRATION APPENDIX IV.13 Experiment 2.5

2.6 Repeat 2.4

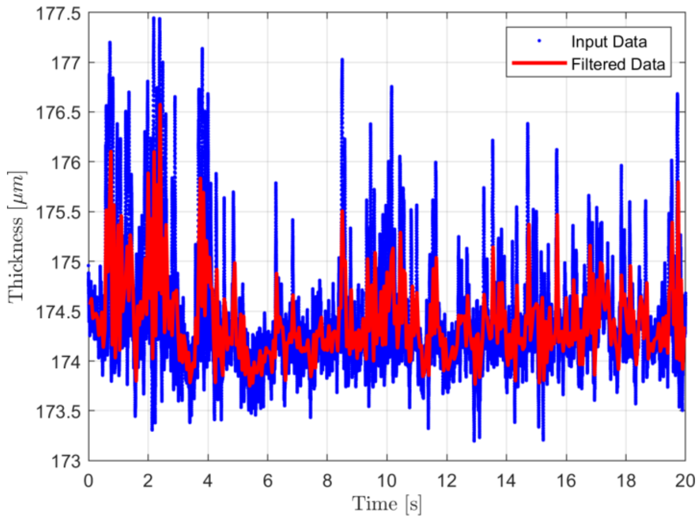


ILLUSTRATION APPENDIX IV.14 Experiment 2.6

The ranges and standard deviations are listed below.

Exp	Range_raw	Std_raw	Range_filtered	Std_filtered
2-1	1.734	0.321	1.550	0.300
2-2	0.862	0.112	0.645	0.094
2-3	0.982	0.124	0.770	0.109
2-4	4.751	0.559	4.287	0.527
2-5	4.925	0.450	4.536	0.421
2-6	4.250	0.566	3.849	0.529

TABLE APPENDIX IV.2 Experiment 2

3. Experiment 3:

   3.1 In an environment of no disturbance, no wind, and constant temperature, and with the rollers off, measure the thickness of the white calibration block at 1000 Hz for 60 s, calculate the range, standard deviation.

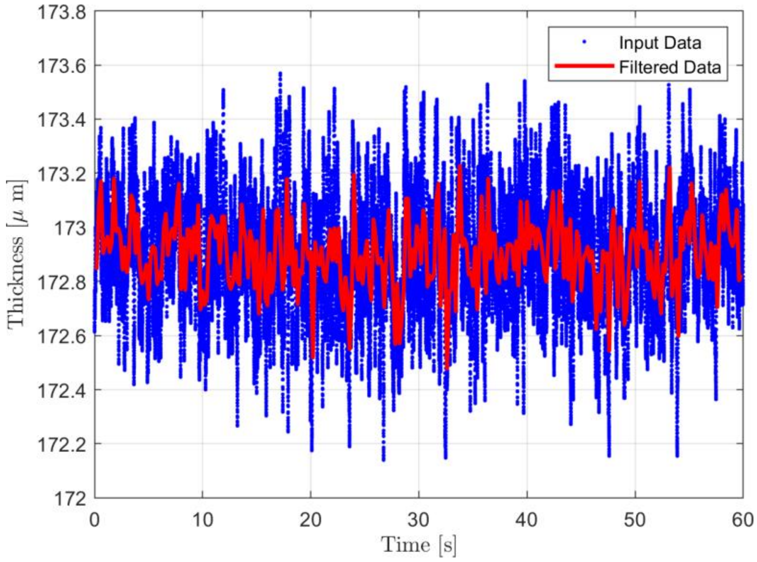


ILLUSTRATION APPENDIX IV.15 Experiment 3.1

   3.2 Repeat 3.1

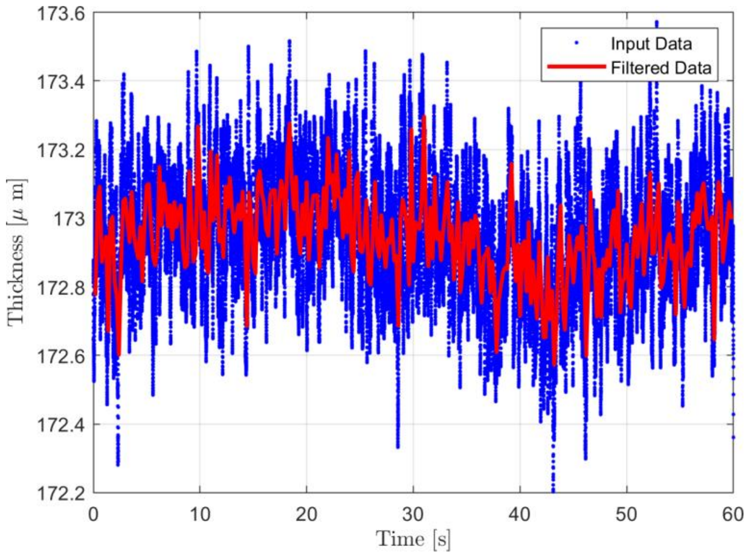


ILLUSTRATION APPENDIX IV.16 Experiment 3.2

   3.3 Repeat 3.1

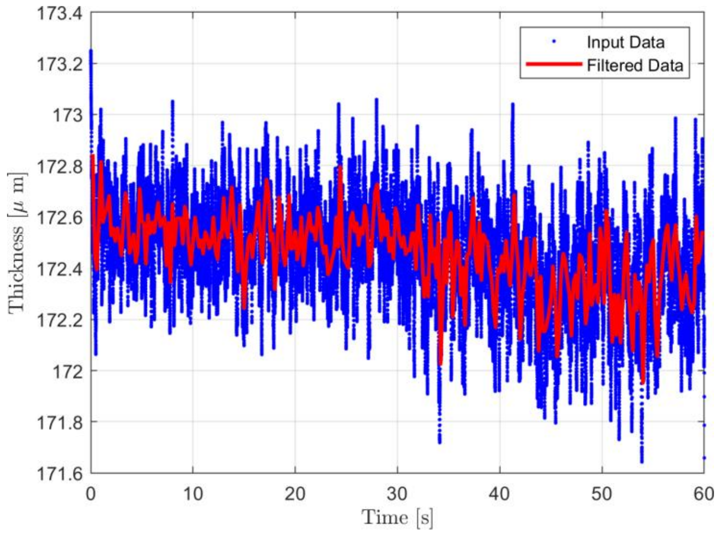


ILLUSTRATION APPENDIX IV.17 Experiment 3.3

3.4 Then turn on the air conditioner (which constantly cools the temperature) and measure the thickness with all other conditions unchanged, calculate the range, standard deviation.

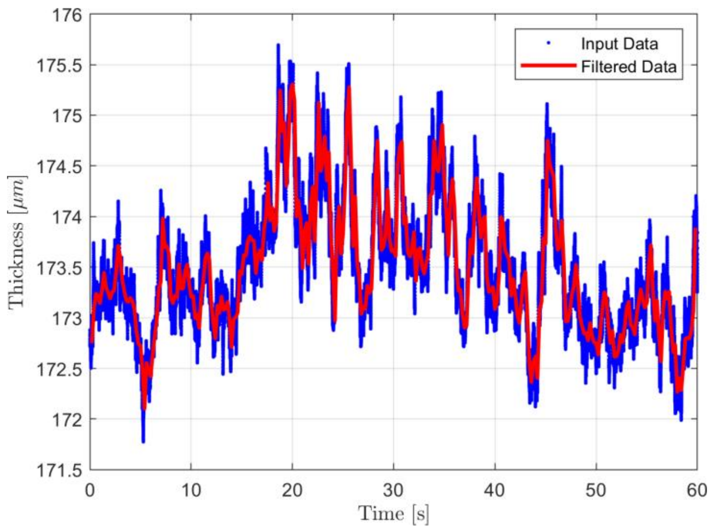


ILLUSTRATION APPENDIX IV.18 Experiment 3.4

3.5 Repeat 3.4

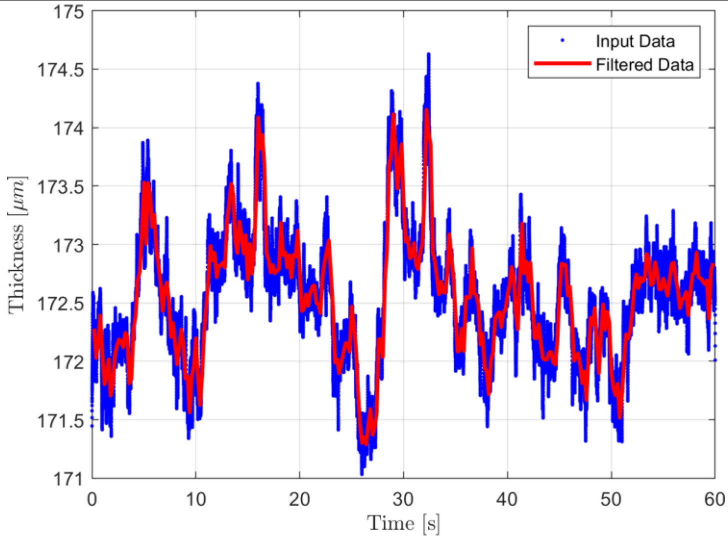


ILLUSTRATION APPENDIX IV.19 Experiment 3.5

3.6 Repeat 3.4

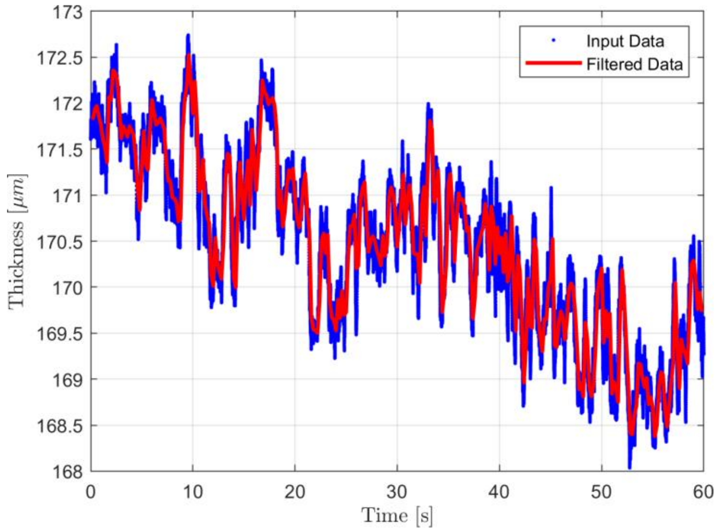


ILLUSTRATION APPENDIX IV.20 Experiment 3.6

The ranges and standard deviations are listed below.

TABLE APPENDIX IV.3 Experiment 3

Exp	Range_raw	Std_raw	Range_filtered	Std_filtered
3-1	1.537	0.214	1.576	0.206
3-2	1.372	0.181	1.240	0.176
3-3	1.602	0.204	1.563	0.198
3-4	3.920	0.655	3.835	0.653
3-5	3.598	0.553	3.501	0.551
3-6	4.705	0.984	4.642	0.982

4. Experiment 4:

4.1 In an environment of no disturbance, no wind, and constant temperature, and with the rollers off, set the time of exposure to 0.12 s and measure the thickness of the electrode sheet at 2000 Hz for 20 s, calculate the range, standard deviation.

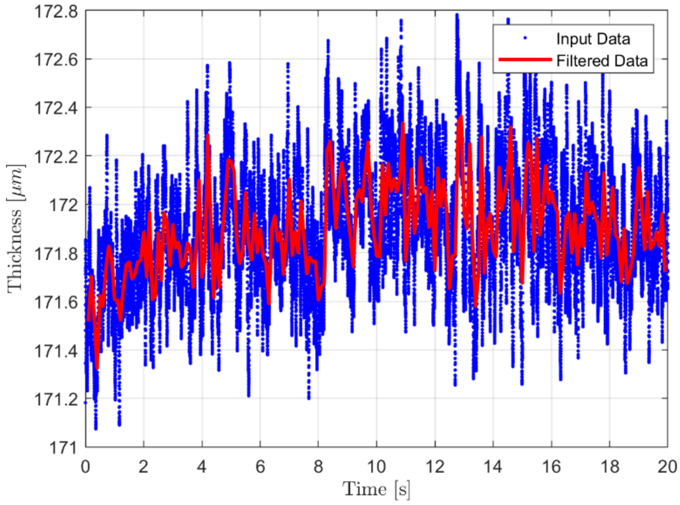


ILLUSTRATION APPENDIX IV.21 Experiment 4.1

4.2 Repeat 4.1

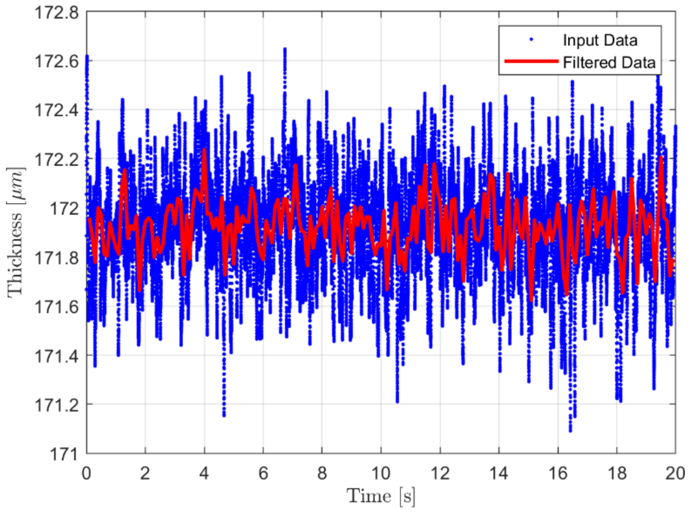


ILLUSTRATION APPENDIX IV.22 Experiment 4.2

4.3 Repeat 4.1

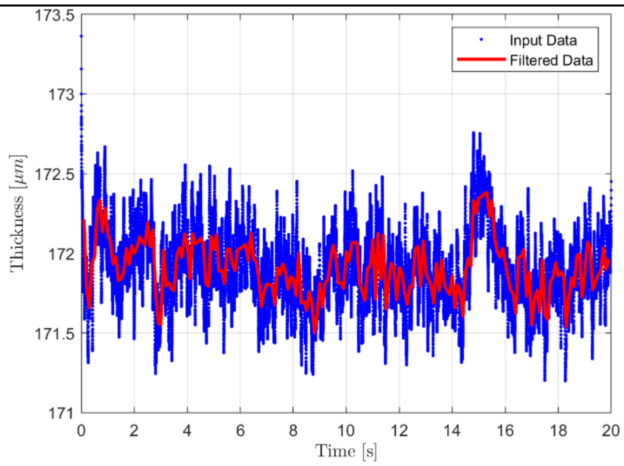


ILLUSTRATION APPENDIX IV.23 Experiment 4.3

4.4 . Then, set the exposure time to 0.09 s and repeat three times with other conditions.

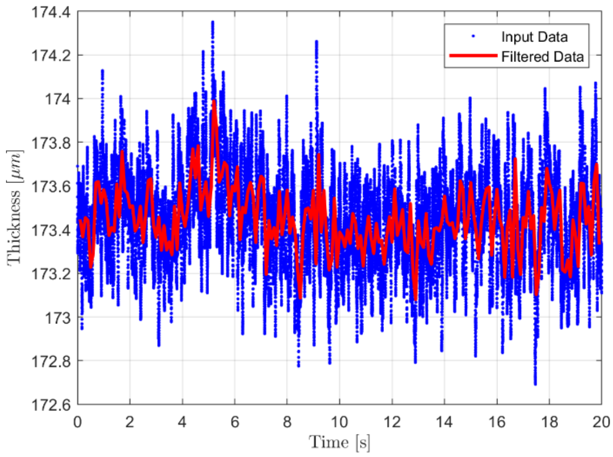


ILLUSTRATION APPENDIX IV.24 Experiment 4.4

4.5 Repeat 4.4

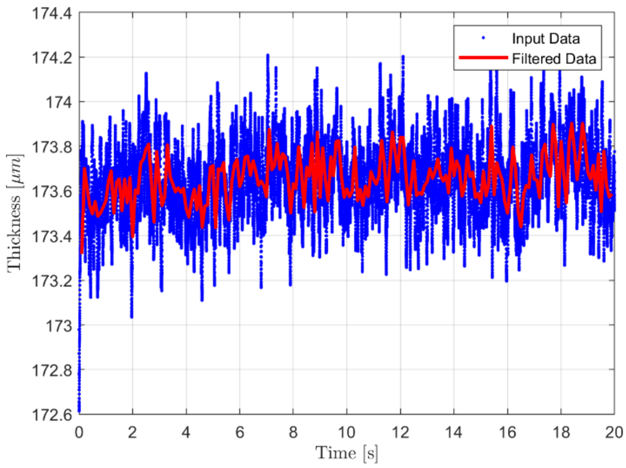


ILLUSTRATION APPENDIX IV.25 Experiment 4.5

4.6 Repeat 4.4

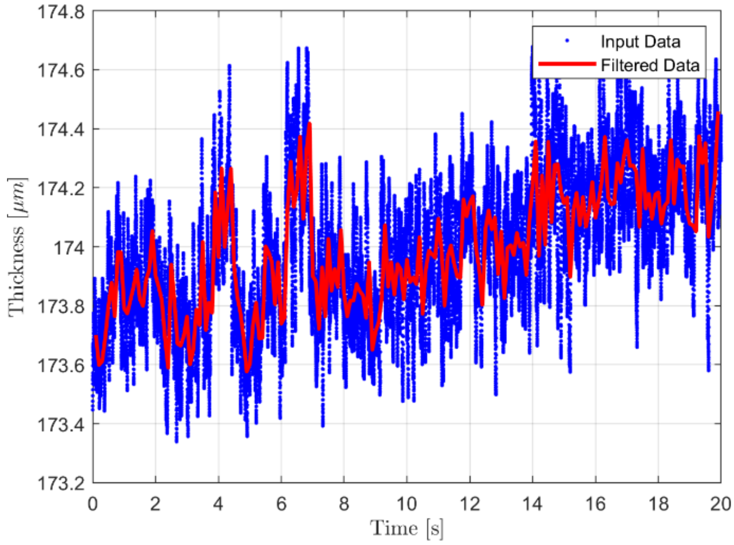


ILLUSTRATION APPENDIX IV.26 Experiment 4.6

4.7 Finally, set the exposure time to 0.06 s and repeat three times with the same conditions.

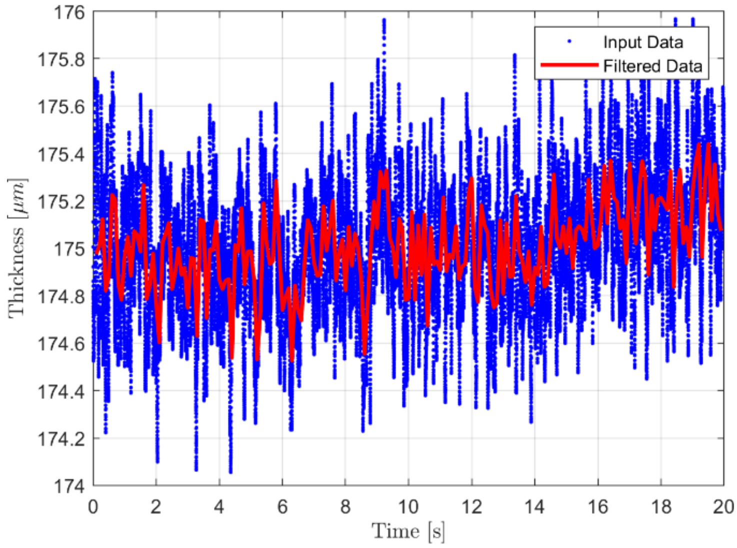


ILLUSTRATION APPENDIX IV.27 Experiment 4.7

4.8 Repeat 4.7

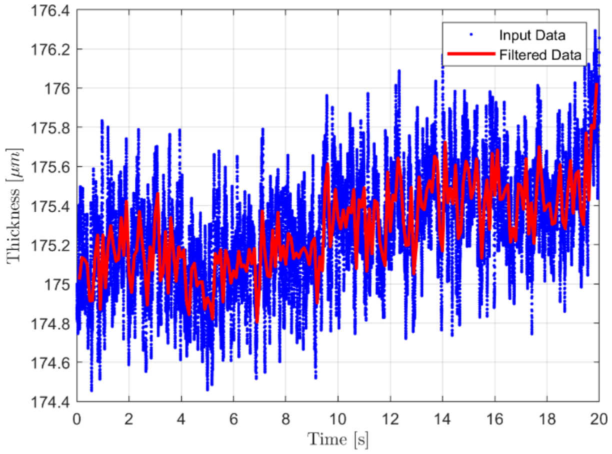


ILLUSTRATION APPENDIX IV.28 Experiment 4.8

4.9 Repeat 4.7

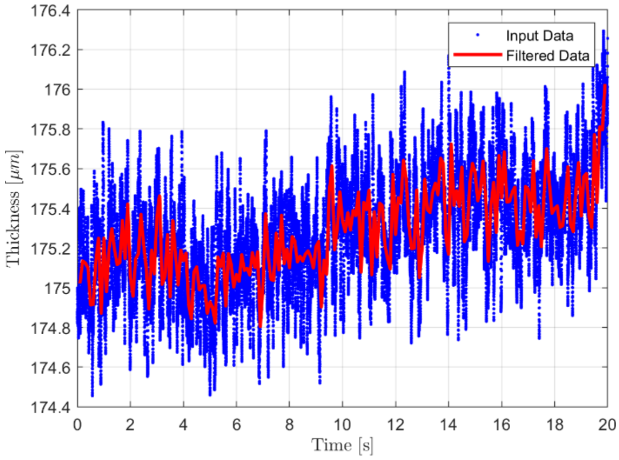


ILLUSTRATION APPENDIX IV.29 Experiment 4.9

The ranges and standard deviations are listed below.

TABLE APPENDIX IV.4 Experiment 4

Exp	Range_raw	Std_raw	Range_filtered	Std_filtered
4-1	1.708	0.266	1.557	0.248
4-2	1.564	0.216	1.318	0.196
4-3	1.558	0.239	1.404	0.223
4-4	1.659	0.223	1.470	0.205
4-5	1.273	0.174	1.375	0.158
4-6	1.401	0.251	1.251	0.239
4-7	1.913	0.289	1.700	0.268
4-8	1.884	0.291	1.640	0.272
4-9	1.807	0.249	1.540	0.228

Appendix IV.III Periodic Experiments

1. Move the C-shaped frame along the lead screw back and forth with a static electrode sheet. This operation scans in the direction that is perpendicular to the moving direction of the coating line. The results for two different positions are shown below.

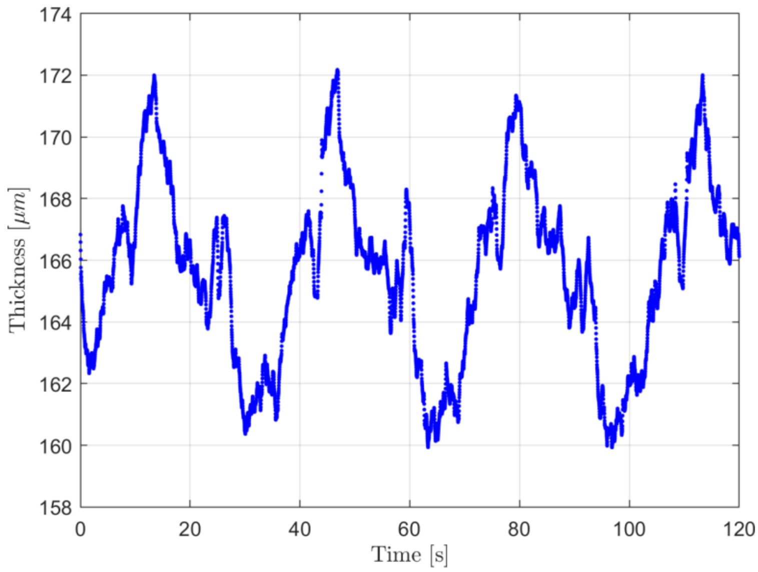


ILLUSTRATION APPENDIX IV.30 Periodic Experiment 1, Position 1

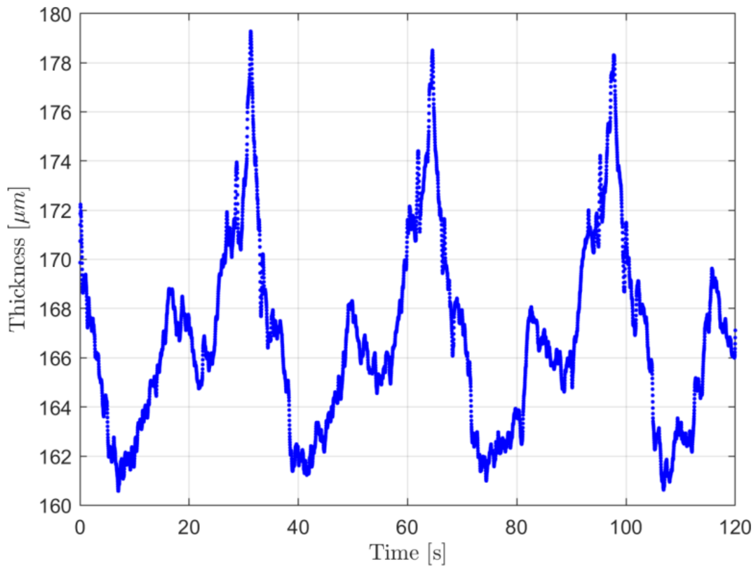


ILLUSTRATION APPENDIX IV.31 Periodic Experiment 1, Position 2

2. Keep the C-shaped frame still with the rollers on. This operation scans the

electrode sheet in the moving direction of the coating line. Since the electrode sheet in this prototype is fixed end-to-end, we expect a periodic pattern. The result is shown below.

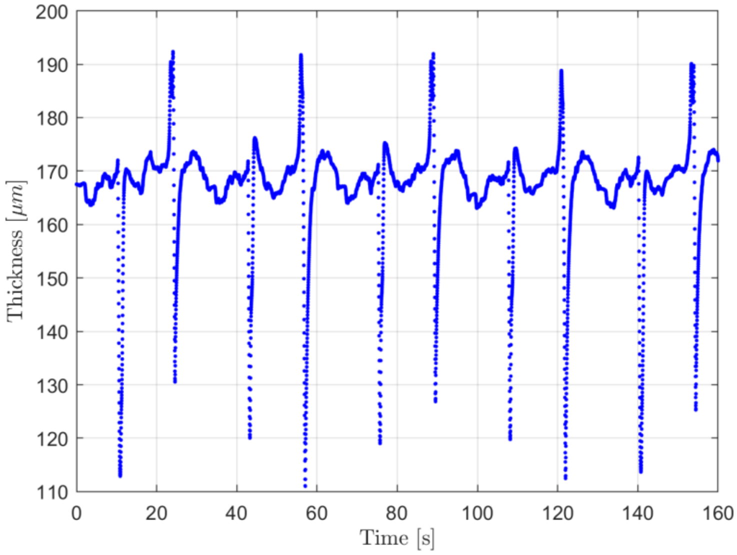
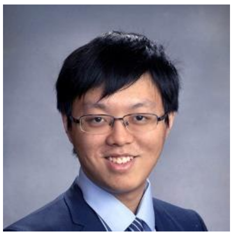


ILLUSTRATION APPENDIX IV.32 Periodic Experiment 2

Biography

Jiajin Wu was born in Shanghai, China. He is currently 22 years old as a senior student majoring in Mechanical Engineering at the University of Michigan - Shanghai Jiao Tong University Joint Institute, expecting to graduate in August 2021 and minor in nothing else. Upon graduation, he will go to the College of Engineering at the University of Michigan Ann Arbor to pursue a master's degree in System Engineering and Design. His dream is to graduate without doing any research, which may result in potential baldness or obesity. As an otaku, he can live without academics, but he cannot survive without anime. To name just a few of his favorite anime characters: Misaka Mikoto, Sakura Yae, Seele Vollerei, Asuka Langley Soryu, Yuigahama Yui, etc.



Zhiyang Chen was born in Hangzhou Zhejiang in 1999. He received a B.Sc. degree in Computer Science Engineering from the University of Michigan in May 2021. He is currently a senior student majoring in Electrical and Computer Engineering at the University of Michigan - Shanghai Jiao Tong University Joint Institute and is expected to graduate in August 2021. After graduation, he will be joining the University of Toronto to pursue a master's degree in Computer Science. His research interests are broadly program languages and security. He is constantly interested in regional politics and the global economy. His hobbies include swimming and badminton. His dream is to retire as early as possible.

Zefang Li was born in Jinan, Shandong, China in 1998. He is with the University of Michigan - Shanghai Jiao Tong University Joint Institute. He is currently a senior student majoring in Mechanical Engineering and minoring in Computer Science. Upon graduation, he will be joining Carnegie Mellon University to pursue a master's degree in Mechanical Engineering (or EPFL to pursue a master's degree in Robotics, the decision is not finalized yet). He is interested in soft robotics and would like to pursue a career in academia or industry in related fields such as wearable electronics, medical robotics, and microelectromechanical systems. His hobbies are swimming, seal carving, and playing Ukulele.

Yuenong Ling was born in Shanghai, China, in 1999. He received his first B.Sc. degree in Engineering Physics from the University of Michigan. He is currently a senior student majoring in Mechanical Engineering at the University of Michigan - Shanghai Jiao Tong University Joint Institute and is expected to graduate in August 2021. Upon graduation, he will join the Massachusetts Institute of Technology to pursue a master's degree in Aeronautics and Astronautics. His research interests include bubble dynamics, numerical simulations, computational fluid dynamics (CFD), and turbulent flows. He is an avid fan of sports, especially soccer, football, and all college sports. He is a proud season ticket holder of UMich football and basketball. Go blue! His dream is to become a perennial season ticket holder of Liverpool.

上海交通大学 毕业设计（学士学位论文）
单独工作报告

SHANGHAI JIAO TONG UNIVERSITY

CAPSTONE DESIGN (BACHELOR’S THESIS)

INDIVIDUAL CONTRIBUTION REPORT

Student Name: Yuenong Ling

Student ID Number: 517370910112

Major: Mechanical Engineering

First, I want to thank my excellent teammates for their contributions to this project. Without their outstanding jobs in designing, manufacturing, assembly, and testing, I would not be where I am now. In this project, I am responsible for the generation of engineering specifications, the analysis of our hardware designs, the design of validation tests, helping to assemble the final product, carrying out the actual tests, and making media materials, including rendering concept designs and making advertising videos for the project. For the analysis specifically, I used ANSYS Mechanical to simulate the motion of our C-shaped frames to help the designer pinpoint the weakness of the current design and subsequently improve it accordingly. It also helped validate whether the components satisfy our engineering specifications before manufacturing. I roughly put more than 25 hours and even more than 30 hours into the project each week during peak weeks. While it is a heavy workload, I enjoy the process wholeheartedly as I amassed a ton of experiences of initiating a project from mere customer requirements and finally developing it into an actual product.

The project was not an easy one right from the beginning. The customer requirement itself was hard to realize in the first place. Measurement accuracy within micrometers was unimaginable for us before this project. Furthermore, we felt and knew the intense working style and high requirements from our sponsor CIML after visiting their factories in Ningde. After thorough literature reviews and brainstorming, we set the sensor we would like to use and the primary moving mechanism suitable for the engineering specifications. The initial design was carried out by my teammate Jiajin Wu and Zefang Li. They laid a solid foundation for further improvements.

To improve the design as much as possible and know where to improve, we decided to use finite element analysis (FEA) to simulate the working conditions of the product. The challenge of the simulation was multifaceted. Luckily, I addressed them in time to help the improvement of the design. First, simplifications must be made to make the simulation doable in terms of time and storage space. The sensors and their fixtures are incredibly complicated to mesh, which is essential for the FEA. As much as we like to keep the structure intact, we did not have hardware good enough to carry it out. Therefore, I used the remote mass functionality to replace the complicated sensors and their fixtures during the simulation. It was valid as tightly fixed to the fixtures, and sensors move along the same trajectories as the center of mass of the whole structure. Second, the quantity to be minimized was quite vague. Although we did know that the overall goal was to mitigate vibrations, we did not have a clear idea of which quantity was. Fortunately, as the one who came up with relevant engineering specifications following guidelines, after communicating with both sponsors and teammates, I set it to be the amplitude of vibration at the tip of the C-shaped frame. While we did not need its exact value, we stressed its trend when we changed some parameters and the time needed for the vibration to die out. It aided the design because it determined whether a change in specific parameters positively or negatively impacted the result. Finally, setting up the simulation itself was a challenging task. As the only one having some background in numerical simulations, I was naturally the best option to take the burden. However, I was not familiar with FEA software at all. While I knew quite a bit about the mathematical formulations and background of numerical simulations, I barely used commercial software because there was usually no need for that in my previous experience. Therefore, I spent most of my time learning how to use the correct parameters to set the simulation up using ANSYS. Thanks to ample and high-quality resources online, I made it on time and succeeded in aiding my teammates to improve the design.

I also played an active role in advertising our project. First, I rendered the concept design based on the initial Solidworks design to make the product realistic and attractive as much as possible. It ends on our presentations and poster as the face of the project. I also produced the advertisement video at the end of the semester. It does an excellent job of giving a brief yet informative introduction to people with little background in the technical side of our project. I am proud of my achievements because I swiftly picked them up to fulfill all requirements as someone with zero background in all these areas just three months ago.

I learned most in this project that it is acceptable to be an auxiliary member of a team and still do a fantastic job. As someone usually quite active in group projects, I was more accustomed to taking a leading role. However, since mechanical design is not one of my most vital skills and my teammates happened to be experts in this area, I chose to step back a little bit and be a helping hand to others. On top of helping teammates assemble the hardware and conducting necessary experiments, I did most of the perhaps less technical jobs but arguably equally or even more important than the design itself. In a team project, there must be someone playing such green-leaf roles. Surprisingly, I accustomed to the role quite fast and felt proud to be one. I learned a lot, ranging from using professional editing and rendering software to designing aesthetically pleasing figures and videos along the way. These will be valuable skills in my future endeavors as modern engineers and scientists need these tools to promote their work.

In terms of things that I can do better, the first popping out of my head is to be a better communicator. I wasted a ton of time confirming the design and analysis requirements with sponsors and teammates due to a lack of efficient communications. The best thing I can do is perhaps being as candid and straight as possible in every conservation.

In all, it is an incredible journey to finish this project, and I hope I can take advantage of the skills and lessons I learned in this project in my future endeavors!

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SHANGHAI JIAO TONG UNIVERSITY

CAPSTONE DESIGN (BACHELOR'S THESIS)

INDIVIDUAL CONTRIBUTION REPORT

Student Name: Jiajin Wu

Student ID Number: 517370910229

Major: Mechanical Engineering

My name is Jiajin Wu. I am a senior student major in mechanical engineering at the University of Michigan-Shanghai Jiao Tong University Joint Institute. By convention, the capstone design is assigned by groups. The thesis of our capstone design is "Non-contact thickness measuring device for coating process in battery manufacture." My group members are Zefang Li (major in Mechanical Engineering), Yuenong Ling (dual degree in Mechanical Engineering and Engineering Physics), and Zhiyang Chen (major in Computer Science). Our thesis is a multi-disciplinary program relevant to mechanical engineering, electrical engineering, and computer science, while our group members also have various academic backgrounds.

Since we only have four members, and our thesis is a comprehensive campaign consisting of hardware and software, the division of work is very complicated. Generally, we divide our work based on two principles: capability and equality. Zefang Li is the leader, responsible for the team affairs, the assembly, and prototype testing. Yuenong Ling is responsible for the simulation of working conditions and assisting Zefang Li and me. Zhiyang Chen is in charge of the software part of the measuring system, including the transmission of data and user interface design. Since I am pretty good at using computer-aid design software (like SolidWorks) to build 3D models, my primary duty is to design the measuring system's mechanical (hardware) parts.

Designing the mechanical parts of the whole measuring system is not an easy job. There are several steps you must undergo before the release of the final product. The first step is to be familiar with the engineering specifications and brainstorm the concept of design. For this project, the essential specifications are stability and maneuverability. Since we have chosen the confocal displacement sensor, our device should be as stable as possible to guarantee the repeatability of the high-precision thickness measurements. Meanwhile, since we must detect multiple points along the parallel and perpendicular direction of the product line, while the sensor we have chosen can only detect the thickness of a certain point, our device should have a specific mechanism for maneuverability. Based on the last two requirements, we have brainstormed several design concepts and evaluated their advantages, disadvantages, manufacturability, reliability, and cost before making the final decision.

The second step is to build the authentic 3D model with computer-aid design software. The more accurate you have built your model, the easier you can find the small but fatal design mistakes in advance. The modeling process requires you to elaborate on the dimensions of all components and define the appropriate mates to assemble them while getting rid of the interference and misfunction of parts. I also have to determine the models of the standard parts that we would like to use, check their dimensions, and contact the vendors to purchase them. If it cannot be found in the market, I would contact the manufacturer to customize the parts we need. Also, we have manufactured some of the parts by ourselves. Our leader Zefang Li has helped me purchase necessary parts and contact vendors for detailed information in this step.

The last step is to inspect and refine your design continuously. I have always published the current progress to the shared folder to verify and brainstorm with my teammates. In this process, Zefang Li and Yuenong Ling have helped me a lot, as they have proposed many novel ideas and solutions to the existing problems. Also, Yuenong Ling has simulated the performance of my design under actual working conditions with the finite element methods provided by ANSYS. After a dozen iterations, we have determined the final design of our prototype.

Since I should be the most familiar with our design, I have also shouldered the responsibility to assemble the components of our device. In detail, to assemble the parts as what we have designed and construct the hardware part of the measuring system—acknowledgment to Zefang Li and Yuenong Ling for their assistance in this time-consuming process. I have also participated in the testing process to make the whole system, including the sensors, motors, and moving mechanism, work properly.

I have to admit that even if we have already inspected the 3D model design many times, there are still many unexpected things during the assembly process. For example, the quality control of customized parts is so terrible that some of the actual product's dimensions turn out to be far from our expectation, resulting in the vulnerability, unreliability, or even misfunction of our measuring system. This experience taught me that when you ask someone else to manufacture something for you, you would better list all your requirements no matter how simple and obvious they are from your perspective. Otherwise, what others are thinking about is likely absolutely different from yours and leads to failure consequently.

Another lesson I have learned is always trying to think a step further about the procedures after your design. To be more specific, taking into consideration the manufacture (manufacturing process, deviation in dimension), assembly (tools and materials used, techniques to assemble and dismount), and testing (convenience, performance) before it is too late. Sometimes, if you have missed parts of these considerations, you would likely fall into some trouble in the following steps paying for your carelessness. I forgot to design the calibration stage for our sensors, and it may cause uncertainties or even errors during the calibration and measuring processes. Though I have reflected on myself and make a temporary complement, the overall effect of calibration is still unsatisfactory.

We have equally distributed the workload to each member for technical communication parts, including the presentations, reports, slides, posters, brochures, videos, and final thesis. Despite the discrete parts we have cut the technical communication assignments into, everyone is familiar with his part and other parts, which I think is quite good if everyone knows everything.

In a nutshell, although we only have four people, my teammates and I have all contributed a lot to this graduation thesis, and we hope that our efforts would pay off in the end.

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单独工作报告

SHANGHAI JIAO TONG UNIVERSITY

CAPSTONE DESIGN (BACHELOR'S THESIS)

INDIVIDUAL CONTRIBUTION REPORT

Student Name: Zefang Li

Student ID Number: 517021911115

Major: Mechanical Engineering

The division of Zefang Li is as follows. I, Zefang Li, am the team leader and am in charge of logistics, testing the sensor system, assembling the prototype, and technical communication. I also participated in mechanical design, purchasing components,

For logistics, I am responsible for communicating with the sponsor, the faculty instructor, one of the suppliers (Shenzhen LightE), the laboratory coordinators, and the TAs. At the beginning of the summer 2021 semester, I, together with Yuenong Ling, went to Ningde in Fujian Province to visit the coating lines, which is the application scene of this project, figured out the sponsors' requirements of this project, and transmitted what I saw to my teammates (Jiajin Wu and Zhiyang Chen), which served as the starting point of this project. I also communicated and cooperated with Miss Lan Xie from AMIS on my team's and Prof. Jigang Wu's confidential agreement. I negotiated with the sponsors about the details of the project to help the team and the sponsors reach a consensus on the project's milestones and outcomes. Due to the highly flexible schedule of the sponsors, I also communicate with the sponsors to schedule the weekly meetings, and I also recorded minutes for weekly meetings with the sponsors and sent them to the sponsors. I communicated with the faculty instructor, Professor Jigang Wu, on meeting schedules, signing confidential agreements, reserving lab spaces, and reporting submissions. Asked by the sponsors from CIML, I also communicated with the sensor supplier, Shenzhen LightE, pretending to be a CIML engineer, to inquire help on test software, setting up sensor systems, designing test experiments, and programming, and transmitted the information to my teammates. To find room for us to build our prototype, I communicated with lab coordinators Dr. Mingjian Li and Mr. Bin Xia at the JI teaching lab to reserve spaces and borrow mechanical and electrical tools. Finally, I also communicated with the TAs to confirm with the sponsors that nothing in our poster, brochure, and video violates the confidential agreement and to submit the introduction articles of our project (which was recommended for the expo). I also attended the expo security meeting and was responsible for expo logistics.

For testing the sensors, I designed a test bench to test the sensor system per se. I manufactured the test bench using 3D printing and assembled it with Yuenong Ling. I used the test bench and the test software to conduct the validation experiments (some of them are done with Yuenong Ling and Jiajin Wu) and completed measurement system assessment (MSA), which the sponsors require. After the hardware system has been shipped to campus, I, together with Jiajin Wu and Yuenong Ling, tested the sensors when fixed to the C-shaped frame, which includes four experiments designed by we three together. The experiments are conducted by myself and some parts by Yuenong Ling, and Jiajin Wu processes the data. I also designed and manufactured a calibration block holder that supports the calibration block during calibration on the C-shaped frame.

For assembling the prototype, I assembled the rollers and adjusted their heights with Jiajin Wu multiple times, fixed the sensors to the C-shaped frame, and fixed the C-shaped frame to the slide rails. I also replaced the rails from the sponsors with the newly arrived rails and rail supports. With Jiajin Wu and Yuenong Ling, I assembled the foot cups to the baseboard and assured its height and horizontality multiple times. I also cut up to 5 electrode sheets with a length of about 3 m, strengthened them by sticking paper tapes to them on all eight edges, and fixed them to the rollers. I also repaired over three broken electrode sheets. I developed the techniques for using, repairing, and fixing electrodes, making our prototype stable and portable. I assembled and enabled the motor that drives the rollers.

For technical communication, I was in charge of everything except the short video. After each of the design review guidelines was released, I always make a to-do that contains clear structures of the presentation and a report with detailed requirements from both the guideline and the grading sheet to help our team with the structure and division of work. I completed an average amount of work in presentations and reports, and I undertook an above-average workload. I wrote the brochure and polished it with Zhiyang Chen and Jiajin Wu in preparation for the design expo. I completed the major part of the poster while Zhiyang Chen wrote the “validation plan” part. I also made the group photo and wrote the introduction article for recommended groups in the expo.

I also participated in mechanical design and purchasing in minor roles. I assisted Jiajin Wu in polishing the first several versions of the C-shaped frame. I also purchased all the screws and nuts, all the 3D printed parts. For the first half-semester, I am responsible for receiving components mailed from the sponsors.

To conclude, my workload is the same as the other three team members, and the workload is evenly distributed among the whole team.

During the graduation thesis, the primary structure of the hardware system was specified by the sponsors, so the design flexibility was relatively small. The whole solution naturally came from the nature of the application in the coating lines. The design work is not complicated but needs consistency, i.e., one person does far better than two. Therefore, although I initially participated in mechanical design, I later left this job to Jiajin Wu. My primary focus was on validation and testing as well as manufacturing. During the testing, we found many problems. Systematically testing their nature via control tests and finally solving them were inspired by my long-time stay in the lab and observing and thinking. In this project, I was astonished by the massive impact of tolerances on the assembly process: slight differences can result in severe results. This project also disclosed to me the charm of the manufacturing industry, and I started, for the first time, to think about going to the industry instead of academia.

Concerning skills and knowledge acquired my contribution to the project cultivated a lot on me. As the team leader communicating with different people, the skills of engineering management have been strengthened. To discover the nature of the problems we met, the logic and systematic way of thinking and designing experiments are significant. My working on the experiments strengthened these skills. The central part of gained knowledge came from the assembly process. For the first time, I had a sensible recognition of the impact of tolerance, and later when I design, I will add tolerance into consideration.

Altogether, it has been a memorable experience to work with three great minds at

JI: Jiajin Wu, Yuenong Ling, and Zhiyang Chen. I learned from them the same amount as from the project per se: their passions to do a better job, their creative thoughts, their endeavors to approaching perfectness while compensating with the imperfect reality, etc.

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CAPSTONE DESIGN (BACHELOR'S THESIS)

INDIVIDUAL CONTRIBUTION REPORT

Student Name: Zhiyang Chen

Student ID Number: 517370910165

Major: Electrical and Computer Engineering

First of all, I appreciate my diligent, hard-working, and considerate teammates, who work days and nights to design and build the prototype. Without their efforts, our project would not be where it is now. As the only Electrical and Computer Engineering student in this project, I am working on software development, integrating hardware interface into the software. The software proportion of this project can be divided into three parts: connection, calibration, and measurement sub-systems. Connection means connecting our software with the hardware, specifically, the sensor system. Our software provides easy ways for users to select configuration files, connect the hardware, and read the current sensor status. Calibration means adjusting thickness measurements using standard pieces with known thicknesses. Our software enables users to adjust thickness calculation offset when measuring standard pieces before starting actual measurements. The measuring subsystem is complicated and costs me most of the time. Briefly speaking, it provides two ways for users to take measurements, real-time and multi-point. Thickness data and position, time, sensor readings, and user comments are logged into a spreadsheet, which could be exported or plotted easily. On average, I put more than 24 hours into this project, more than 35 hours during peak weeks. Despite the heavy workload I never experienced in other courses, I feel really satisfied and pleased from the bottom of my heart when it is finished. It is a real-world problem in manufacturing, but we provide our solution built from scratches.

This project did not go well when it started. I thought I would be assigned a software-based project at first since my strengths are programming. Plus, I have some previous research experience in traffic simulation and programming languages, which match some other projects' backgrounds. However, perhaps as if fate had intervened, this hardware-based project selects me. Before this project, I had no background in manufacturing, not to mention a measurement accuracy within micrometers. I started to doubt whether I could contribute to this project. Later, we met our advisors in our first sponsor meeting, Dr. Zhu and Mr. Ma from CIML. Their intensive working style and high requirements surprised me. After getting our majors and strengths, our advisors immediately told us they need a complete measuring system, including software and hardware. Therefore our team is a perfect match.

Additionally, they hoped their engineers would build a mature industry system on top of our prototype; thus, our software should be similar to what they are familiar with. After talking with their software engineers, we finally decided to use C# to build our software. It is a new challenge to me, as I have no previous experience in C#, but I am ready to take this challenge. Nevertheless, before designing our software, we need first to figure out customer requirements and engineering specifications.

After a detailed discussion with our sponsors, we quantify the qualitative requirements listed in the project proposal. This project aims to design and build a measuring system, which costs less than 100,000 RMB, has a size smaller than 1.5 m × 1 m × 2 m, and has a resolution of 0.5μm. With these specifications in mind, thorough literature reviews, and brainstorming, we decide to use a confocal displacement sensor. It is cheap but can only measure one point at a time. Thus we have to design a moving mechanism suitable for our engineering specifications. The initial design was finished by Jiajin and Zefang, while later, it was validated by Yuenong.

After we finalized our sensor choice and first moving mechanism design, I designed our user interface. I confirmed with our advisors that the potential users of our user interface are workers and engineers in a factory; thus, our user interface should be trivial to understand and convenient to use. I finally decided to implement a graphical user interface, which is most common in industrial software among user interface designs. Then I started to design measuring modes for different usage of our measuring system. Two modes have been designed after looking at other industrial software. First, our software should provide users real-time sensor readings. In other words, our software should acquire data from sensors constantly and displayed it to users. Second, our software should allow users to define sampling frequency and total recording time.

I met two difficulties when implementing the two measuring methods mentioned above. First, real-time mode requires constant reading from sensors. However, if we directly put a loop inside button events, it will block other events. As a result, our software will freeze when reading from sensors. Another thread must be spawned to take action to solve this problem, leaving the main thread still responding to other events. Second, after testing, the time delay between hardware and software cannot be avoided. As a result, we cannot depend on C# timers. Instead, we have to rely on a hardware clock to guarantee the accuracy of sampling frequency. Unfortunately, after consulting the sensor provider, the sensor clock is unreadable so far. As an alternative solution, I implement a loop reading sensors' intermediate states, including the number of samplings. By dividing the number of samplings by time intervals, I roughly justify the accuracy of sampling frequency.

Apart from the two modes of measurement, I paid extra attention to user-friendliness and extensibility. Our software has two color themes, light and dark, to suit different working environments. Three ways are provided to select data in the spreadsheet to respond to a large amount of factory data. The data collected can be exported into CSV files for further study or be plotted as time vs. thickness or position vs. thickness.

The most important lesson I learned from this project is how to integrate software into an industrial product. Before this course, almost all of my programs are written and tested on computers. All test cases are well formulated and very convenient to use. However, in this project, debugging is complicated and troublesome. For example, sometimes, I have no idea whether the bug is on the software or hardware side. I have to test every part of our system, hardware or software, to find where the bug is. This experience will shape my skills as an interdisciplinary engineer in the future.

Concerning things that I can have done better, the first thing off the top of my head is developing software synchronous with or even ahead of hardware development. Not every feature should be tested on hardware. Some irrelevant parts could be finished earlier to save time for developing sub-systems that require testing on hardware.

In short, this project is a pleasant and rewarding journey for me! Again, I want to express my appreciation to my teammates, my advisor Mr. Tianxing Ma and Dr. Siqi Zhu, and Prof. Jigang Wu. Their efforts motivate me in this bumpy journey!