113 學年度第一學期工程設計科

Arduino PID 自動跟隨車期末專題報告

113 Academic Year 1st Semester Engineering Design Course

Arduino PID Auto-Following Kart Final Project Report

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30627 廖宏瑨

2025 年 1 月 5 日

目錄

第一節　致老師

親愛的 溫老師敬和：

對於未能及時完全達成公開測試與封閉測試的標準，以及以英語呈現這份專題報告的許多部分，我們深感抱歉。

首先，我們了解這份專案需要大量軟硬體調適與修正，也誠摯希望能夠完成這個有益於我們求學和職涯的專案，但礙於學測與段考等時間壓力，我們僅完成軟硬體的設計與組裝，未能完成最後的調適封測，實在抱歉與可惜。

次者，雖然我了解全數使用中文更具有連貫性並有助於您的閱讀，但軟體開發、LaTeX 與控制理論的技術內容資源以英文較充足，故以英文呈現許多部分，對於由此給您帶來的不便，我深表歉意。

感謝您在二年來課程中的諄諄教誨和耐心支持。

第二節　Division of Labor

To maximize efficiency and leverage each member's expertise, we divided responsibilities as follows:

- 王品翔: An expert in 3D modeling, wiring, structural engineering, and the design of microprocessor-driven bots and karts. With extensive experience in CAD modeling, 3D printing, laser cutting, and microprocessor software development, as well as a track record of winning awards in microprocessor-based bot competitions, he leads the 3D modeling, hardware design, and component production aspects of the project.
- 沈威宇: Specializing in programming and markup languages such as C, C++, and LaTeX, with a strong foundation in advanced mathematics and physics. His portfolio includes developing machine learning-powered financial analysis tools, algorithmic trading systems, Linux virtual machines on Android, microprocessor-driven bots, and software projects in C++, Python, Node.js, and Java. He is responsible for the PID control system, Arduino programming, and the creation of the project report.
- 廖宏璿: Skilled in carpentry, wiring, structural engineering, and programmatic analysis in social sciences. He has contributed to projects like active noise-canceling headphones, microprocessor-driven bots, and social data algorithmic analysis. With expertise in designing and assembling physical structures, wiring microprocessor boards, and breadboards for active motion systems, he focuses on wiring design, wood structure assembly, and parameter tuning.

While roles are defined, teamwork remains at the heart of our approach, with all members actively supporting one another to achieve project goals.

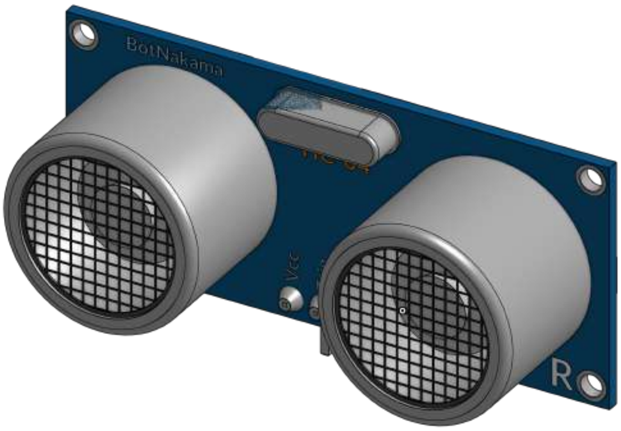
第三節　硬體設計與 3D 建模

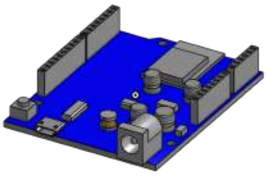
在這次的車輛設計中，我們以自然界的古老生物——鱟作為靈感來源，結合其生物學特性與流體力學特徵，打造出具有前瞻性與功能性的車輛外形與結構。鱟的流線型身體和穩定行走的構造，為我們提供了在設計中平衡美學與實用性的寶貴啟示。

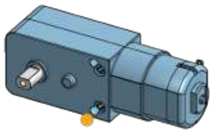
由於跟隨車需要做到即時與大動作地加速與轉彎反饋，我們採用了前驅作為動力系統的核心設計，並在後輪設計採用了萬向滾珠，提高了車輛加速與轉彎時的性能，使車輛在移動時能夠實現靈活的大角度轉彎，增加動力使用效率，並保持配重穩定性。

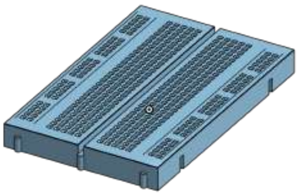
這輛車的設計展現了我們對自然生物演化的體悟，也彰顯了我們對未來交通工具的遠見。通過模仿鱟的仿生設計結構，我們希望這樣的跟隨車設計可以具有提高機動性與增加適用場景的潛能，可以為載人、運貨、倉管、軍事、農業等潛在場景特化使用。

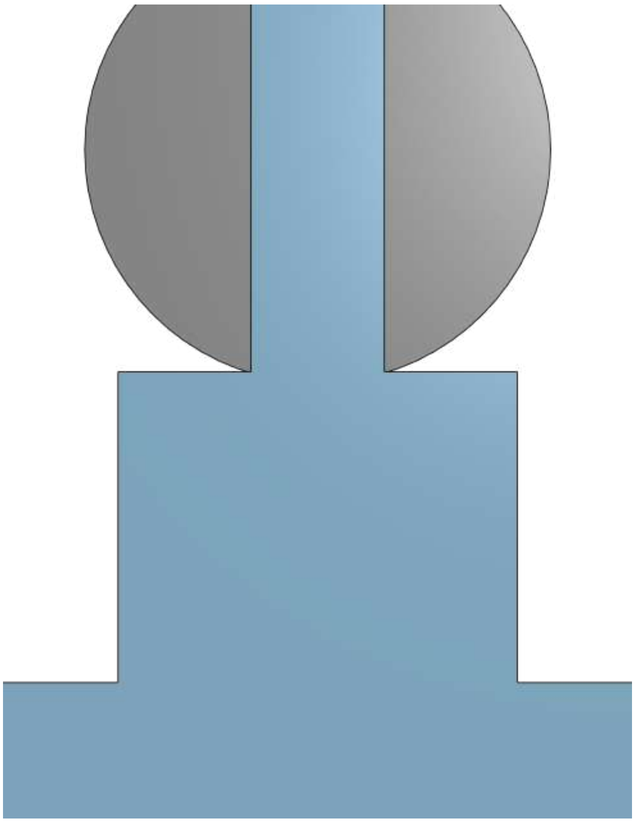
一、　建模圖片

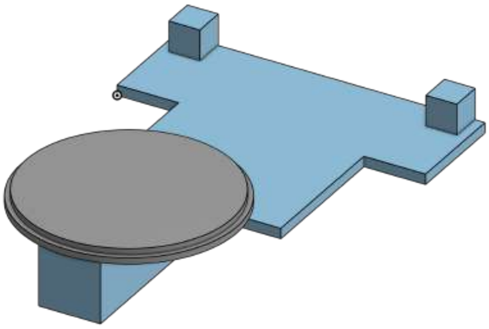

BotNakama
Vcc
R

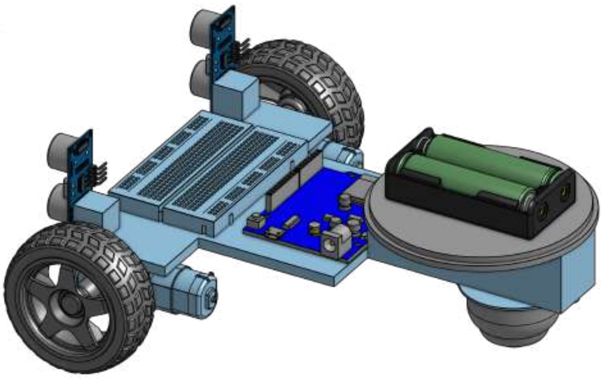


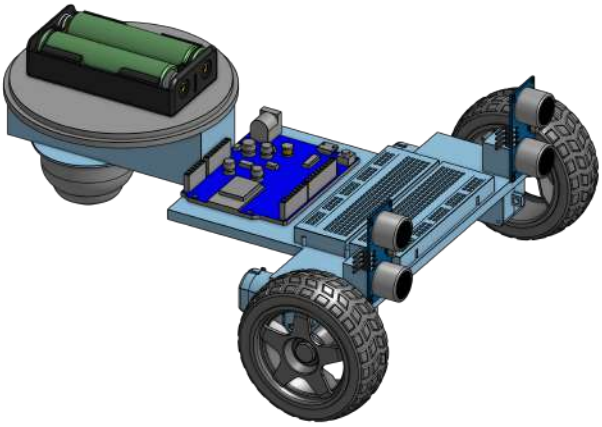


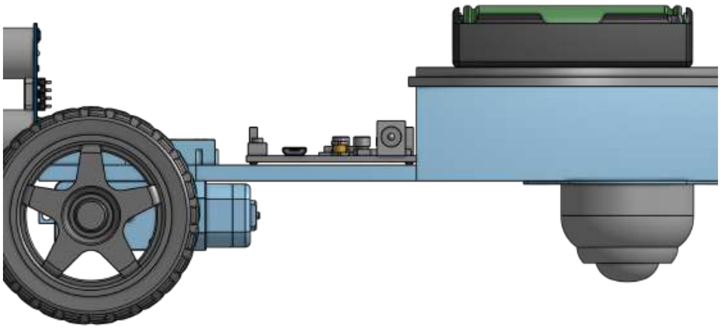


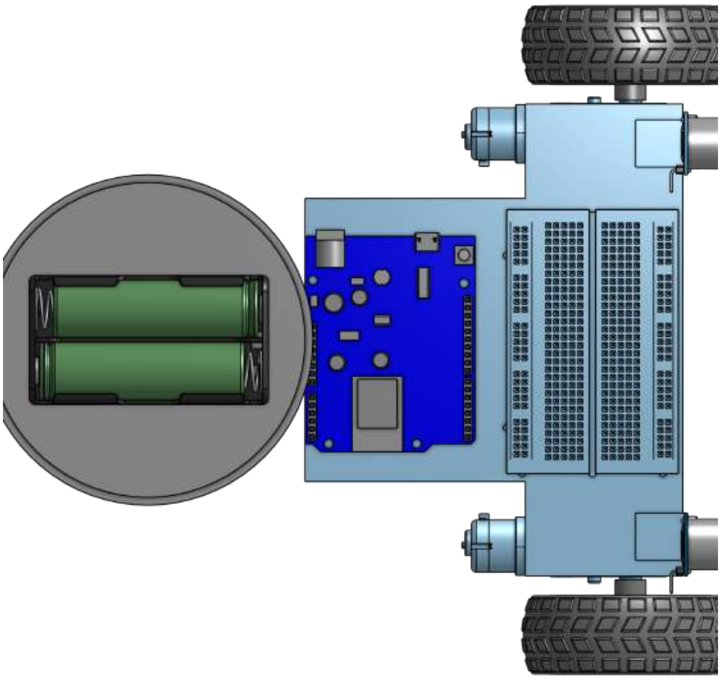


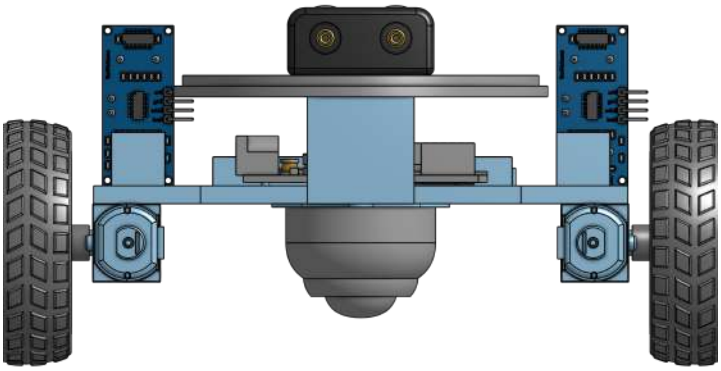


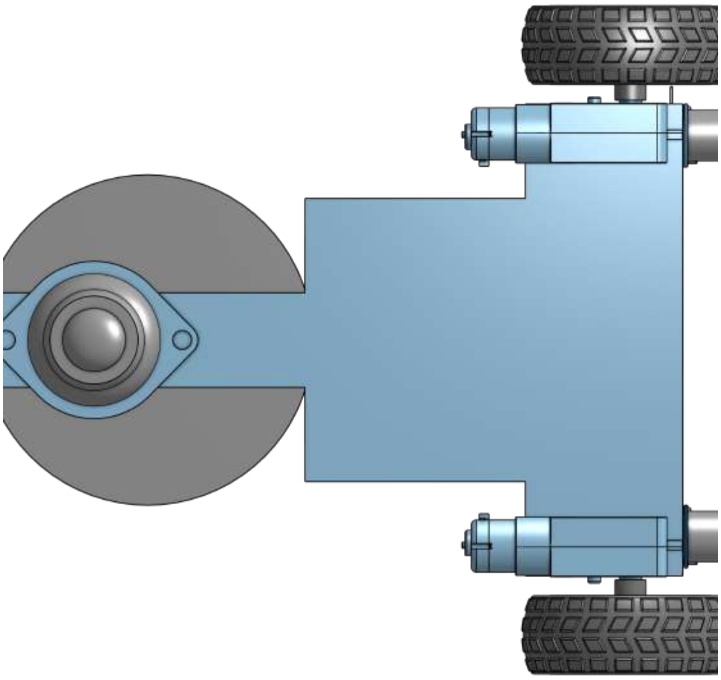


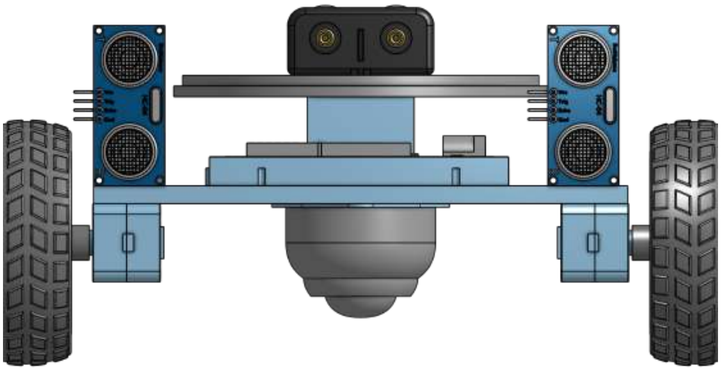




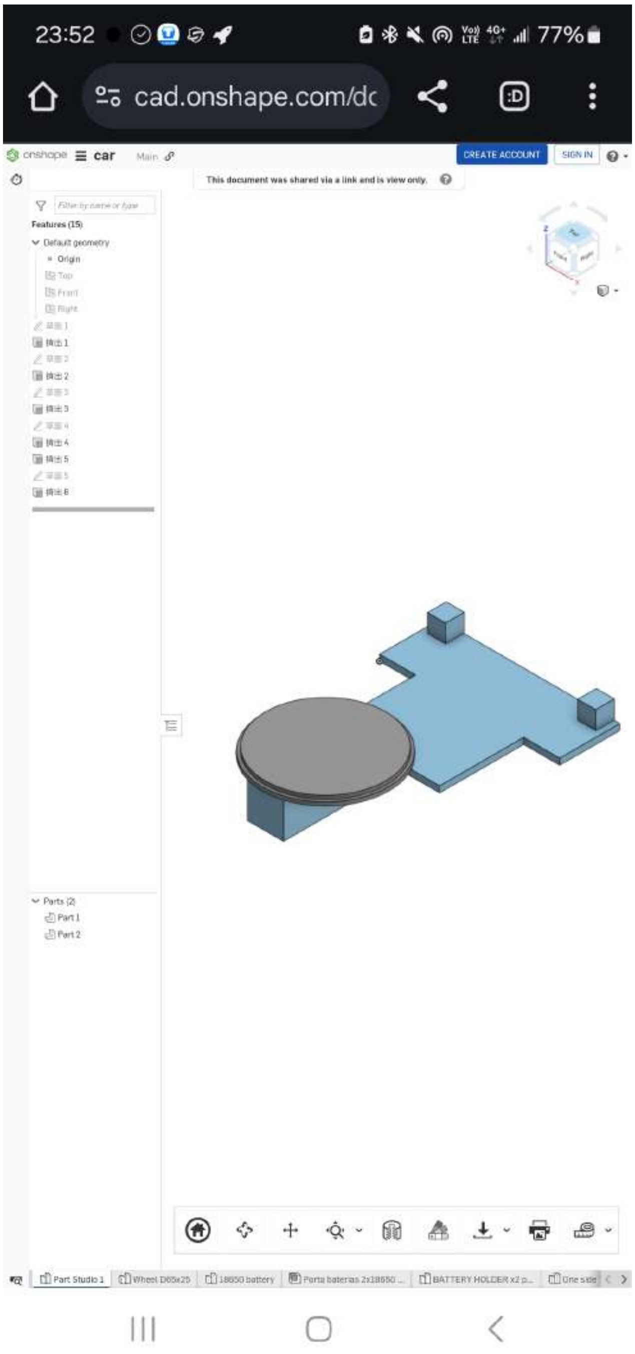








二、 工作截圖



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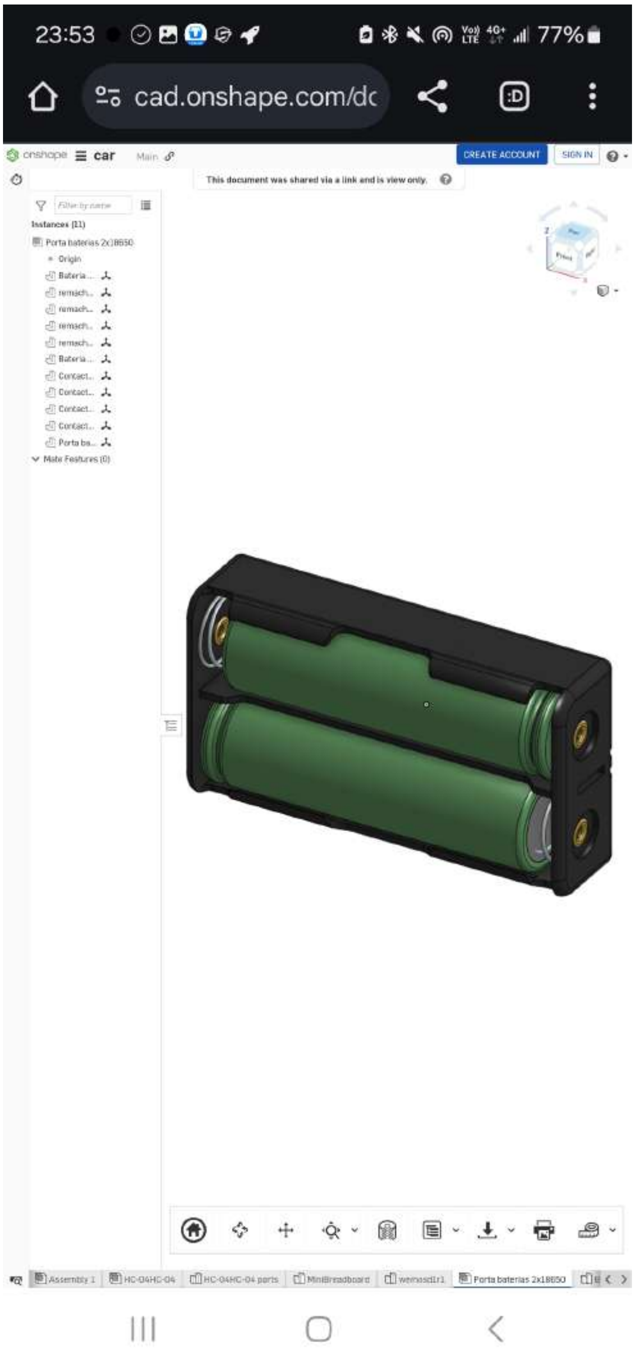
- Default geometry
  - Origin
  - Top
  - Front
  - Right
- 草圖 1
- 擠出 1
- 草圖 2
- 擠出 2
- 草圖 3
- 擠出 3
- 草圖 4
- 擠出 4
- 擠出 5
- 草圖 5
- 擠出 6

Parts (2)

- Part 1
- Part 2



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Instances (11)

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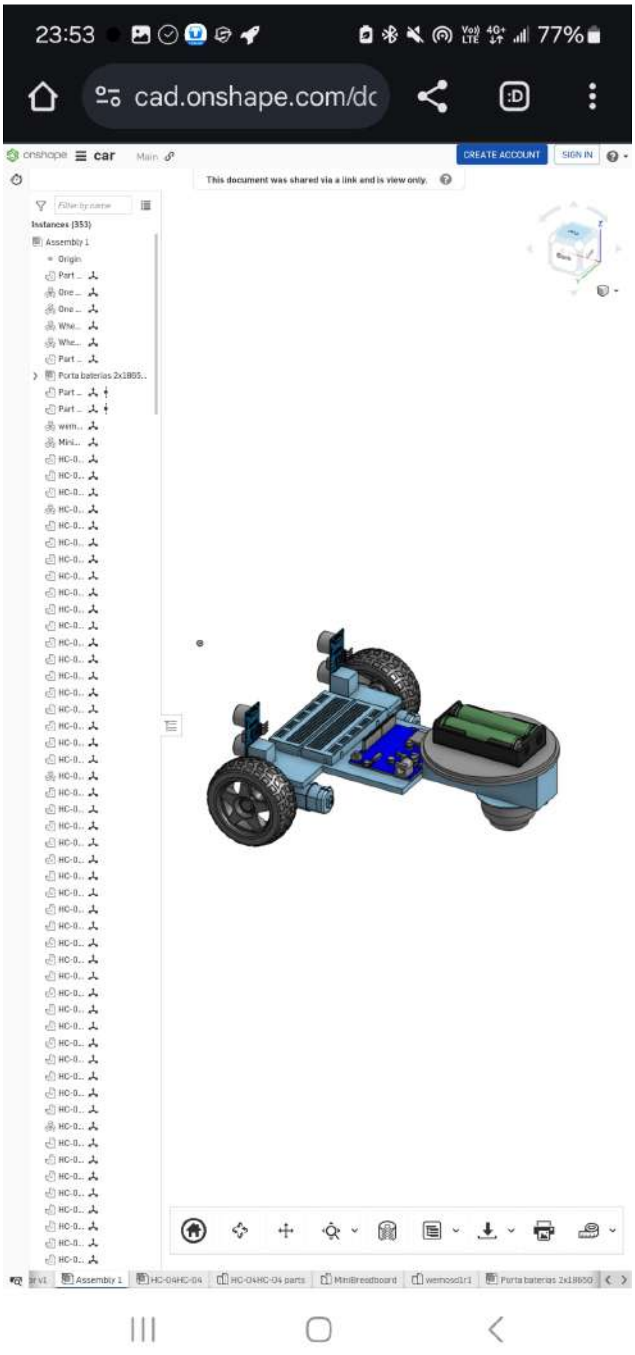
  - remach...
  - remach...
  - remach...
  - remach...
  - Bateria...
  - Contact...
  - Contact...
  - Contact...
  - Contact...
  - Porta ba...
- Mate Features (0)



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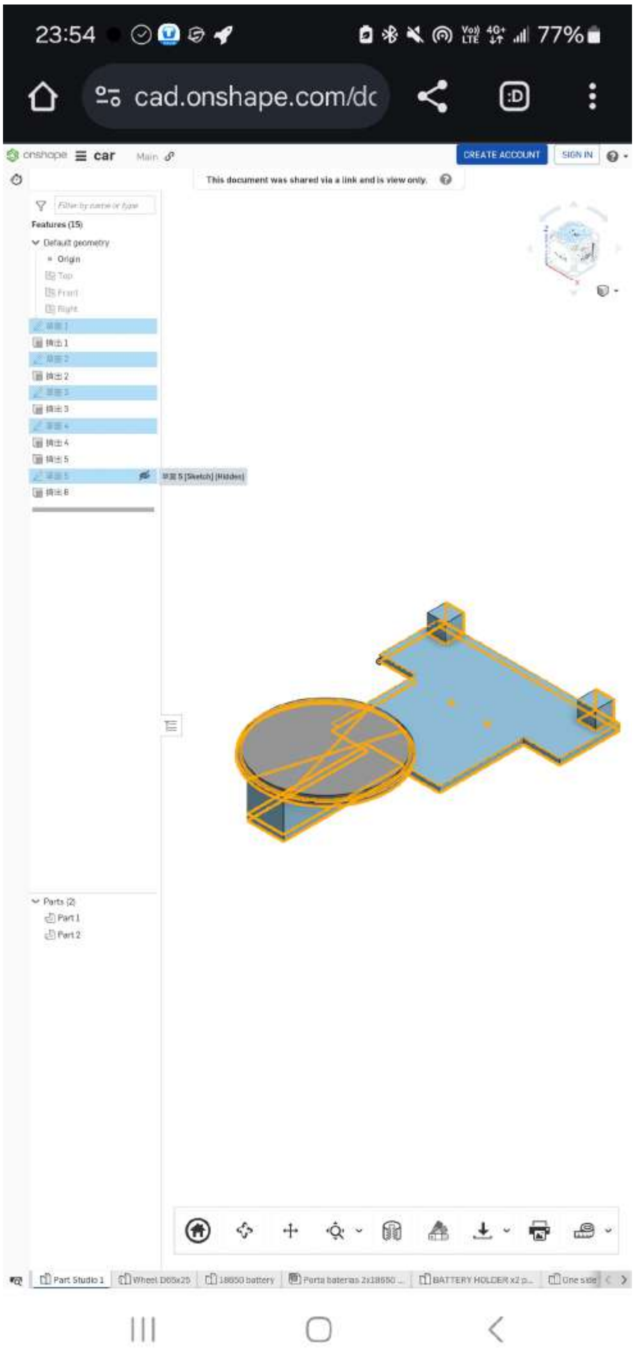

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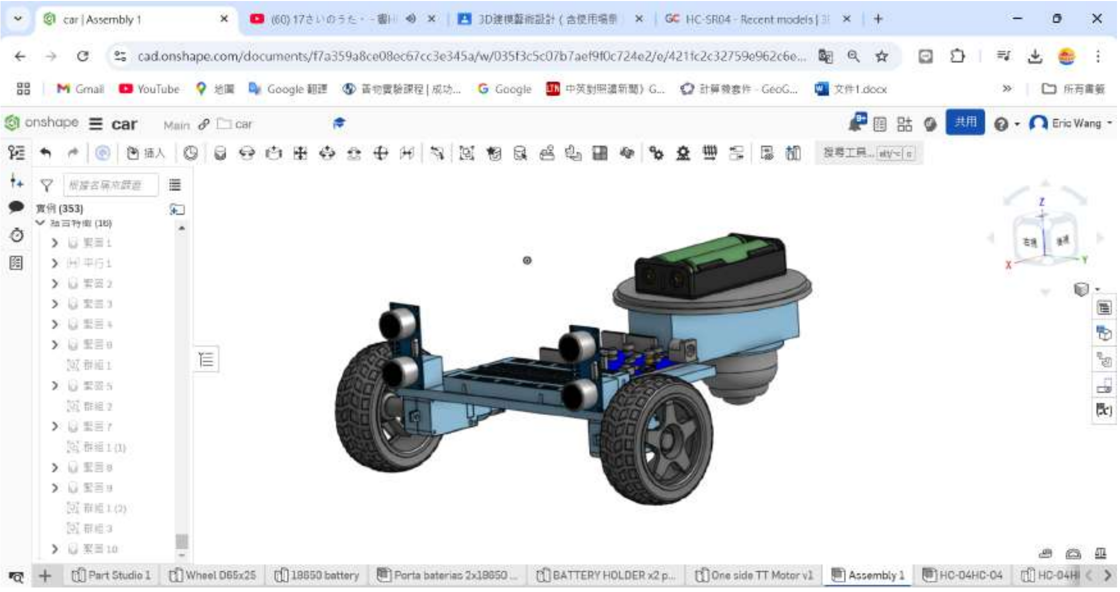
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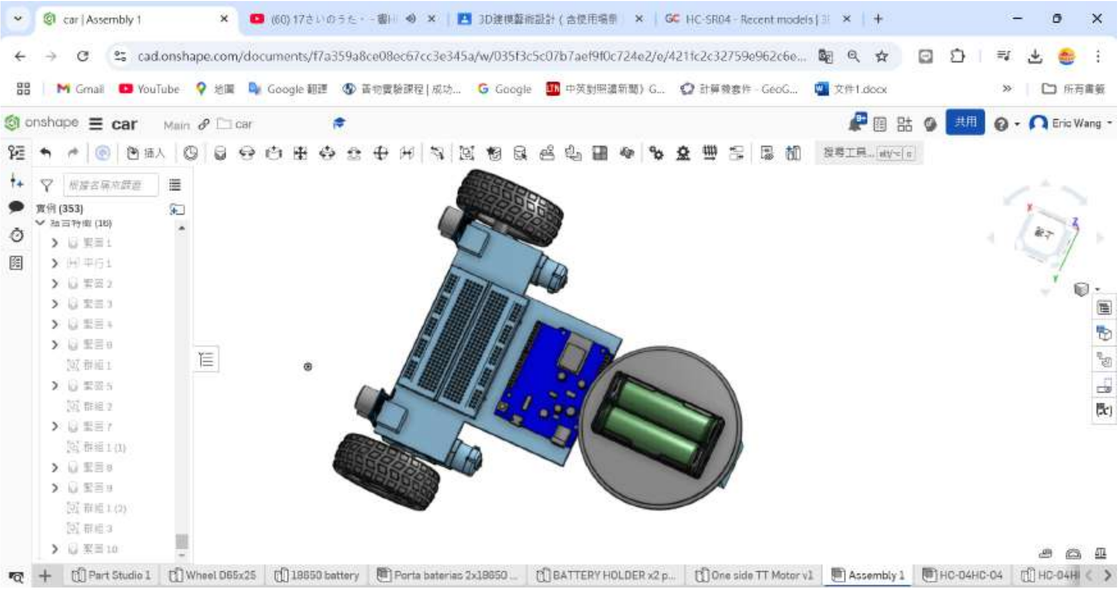
onshape
car
Main
實例 (353)
Part Studio 1
Wheel D65x25
18650 battery
Porta baterias 2x18650 ...
BATTERY HOLDER x2 p...
One side TT Motor v1
Assembly 1
HC-04HC-04
Eric Wang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car
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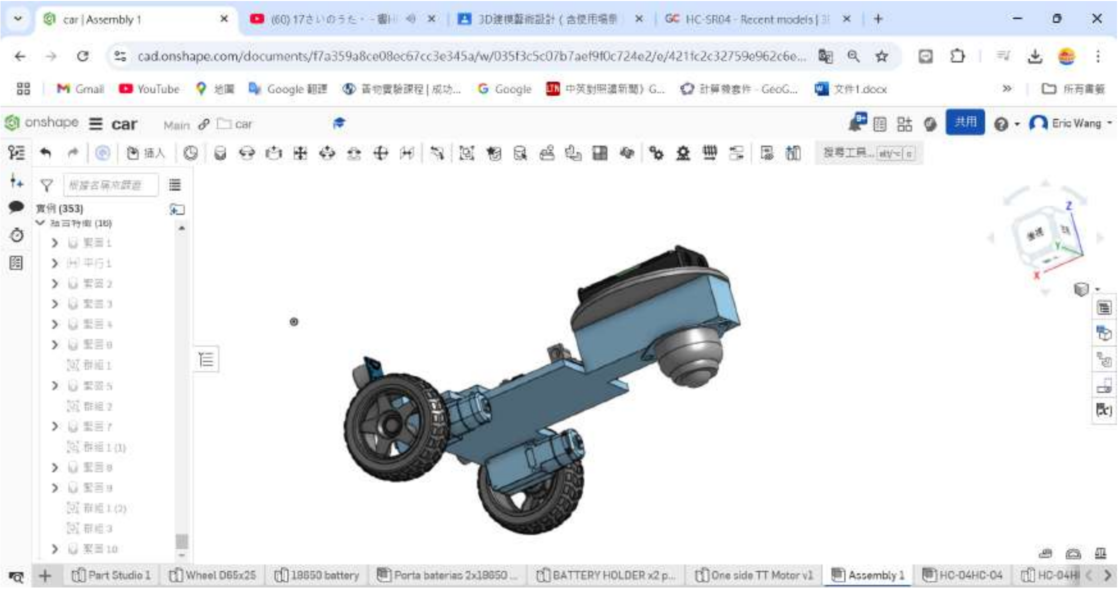
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car
Main
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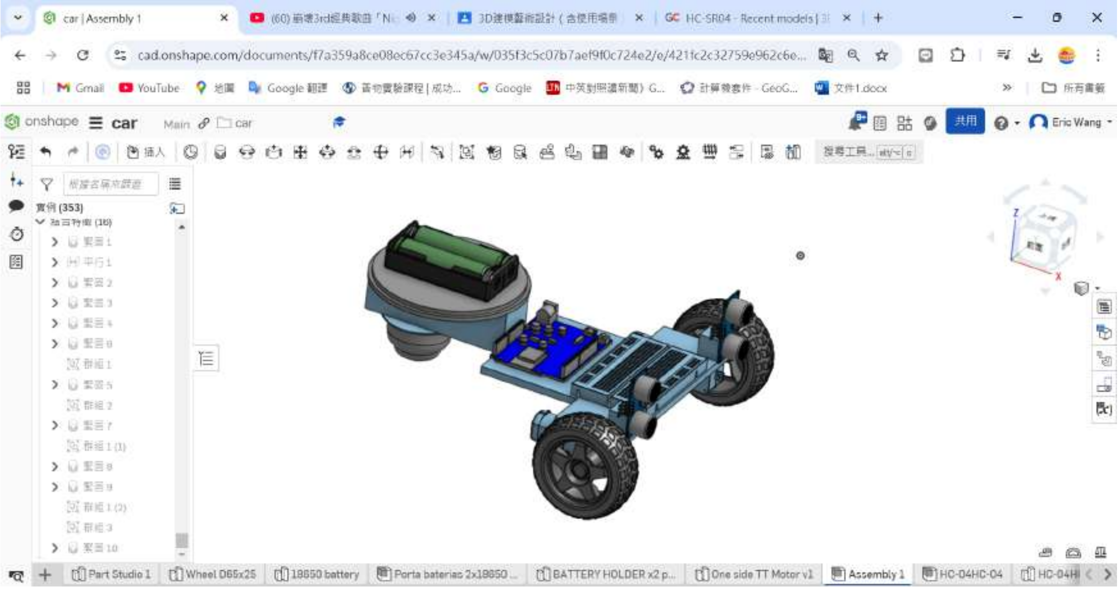

三、 STEP Code

由於字數過多，共 2785701 行，故此報告僅錄部分，完整版請詳見以下連結

- https://github.com/Willie169/PID/blob/main/Assembly1.step
- https://github.com/Willie169/PID/tree/main/Assembly1Parts
- https://cad.onshape.com/documents/f7a359a8ce08ec67cc3e345a/w/035f3c5c07b7aef9f0c724e2/e/4

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ISO-10303-21;
HEADER;
/* Generated by software containing ST-Developer
 * from STEP Tools, Inc. (www.steptools.com)
 */
/* OPTION: using custom renumber hook */

FILE_DESCRIPTION(
/* description */ (’STEP AP242’,
’CAx-IF Rec.Pracs.---Representation and Presentation of Product Manufa
cturing Information (PMI)---4.0---2014-10-13’,
’CAx-IF Rec.Pracs.---3D Tessellated Geometry---0.4---2014-09-14’,’2;1’),

/* implementation_level */ ’2;1’);

FILE_NAME(
/* name */ ’Assembly 1’,
/* time_stamp */ ’2025-01-01T15:34:22Z’,
/* author */ (’’),
/* organization */ (’’),
/* preprocessor_version */ ’ST-DEVELOPER v20’,
/* originating_system */ ’ONSHAPE BY PTC INC, 1.191’,
/* authorisation */ ’  ’);

FILE_SCHEMA ((’AP242_MANAGED_MODEL_BASED_3D_ENGINEERING_MIM_LF { 1 0 10303 442 1 1 4 }’));
ENDSEC;

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#144=SHELL_BASED_SURFACE_MODEL(’HC-04ShapeString011’,(#143));
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#168=DIRECTION(’’,(0.65357109707195,-6.00870875386104E-17,-0.756865127398646));
#169=DIRECTION(’’,(0.512510977513211,0.,-0.858680672851353));
#170=DIRECTION(’’,(0.662573882203037,0.,-0.748996562490374));
#171=DIRECTION(’’,(1.93633660727018E-17,1.,5.80900982181059E-17));
#172=DIRECTION(’’,(-0.0287255166194788,-5.75099039017191E-17,0.99958733720218));
#173=DIRECTION(’’,(-1.87376581651315E-17,1.,5.8294936513743E-17));
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#176=DIRECTION(’’,(0.915644030191286,0.,0.401990062035195));
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#178=DIRECTION(’’,(-0.0230332373689862,-6.04714891480939E-17,-0.999734699796053));
#179=DIRECTION(’’,(2.39142809929948E-17,-1.,5.6369376626345E-17));
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#182=DIRECTION(’’,(-0.998364234827914,-5.73992900415726E-17,0.0571738980346342));
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#184=DIRECTION(’’,(-1.,0.,0.));
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#186=DIRECTION(’’,(1.,0.,0.));
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#189=DIRECTION(’’,(-1.77868683044478E-17,1.,5.85920367675922E-17));
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#191=DIRECTION(’’,(-5.23045763484758E-17,1.,3.18375682121157E-17));
#192=DIRECTION(’’,(-0.9811218143935,-5.74742523009248E-17,0.193390758107018));
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#199=DIRECTION(’’,(0.0236506090873736,-5.74978476150228E-17,-0.99972028522472));
#200=DIRECTION(’’,(-1.,0.,0.));
#201=DIRECTION(’’,(0.,0.,1.));
```

```
#202=DIRECTION(’’,(-5.80366339844372E-17,1.,-1.95230267225937E-17));
#203=DIRECTION(’’,(-0.762925074710322,-5.68989846224568E-17,-0.646486914313237));
#204=CARTESIAN_POINT(’’,(0.,0.,0.));
#205=CARTESIAN_POINT(’’,(2.2765,0.,0.));
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#211=CARTESIAN_POINT(’’,(2.1185,0.,0.059));
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#213=CARTESIAN_POINT(’’,(2.3875,0.,0.0185));
#214=CARTESIAN_POINT(’’,(2.29634052317041,1.71608328067423E-17,0.289160184169284));
#215=CARTESIAN_POINT(’’,(2.483,0.,0.073));
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#220=CARTESIAN_POINT(’’,(2.40159527133997,1.1917626412237E-18,0.165285814019901));
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#222=CARTESIAN_POINT(’’,(2.40157781507673,1.51631839373443E-18,0.16017457531686));
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#233=CARTESIAN_POINT(’’,(2.2535,0.,0.2395));
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#236=CARTESIAN_POINT(’’,(2.4635,0.,0.672));
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#240=CARTESIAN_POINT(’’,(2.2535,0.,0.8));
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#242=CARTESIAN_POINT(’’,(2.2535,0.,1.04));
#243=CARTESIAN_POINT(’’,(2.2535,0.,1.04));
#244=CARTESIAN_POINT(’’,(2.155,0.,1.04));
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#248=CARTESIAN_POINT(’’,(2.15129322327143,2.24322234347462E-18,1.00095195105217));
#249=CARTESIAN_POINT(’’,(2.113,0.,1.0085));
#250=CARTESIAN_POINT(’’,(2.073,0.,0.8));
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#252=CARTESIAN_POINT(’’,(1.946,0.,0.78));
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#255=CARTESIAN_POINT(’’,(1.946,0.,0.7095));
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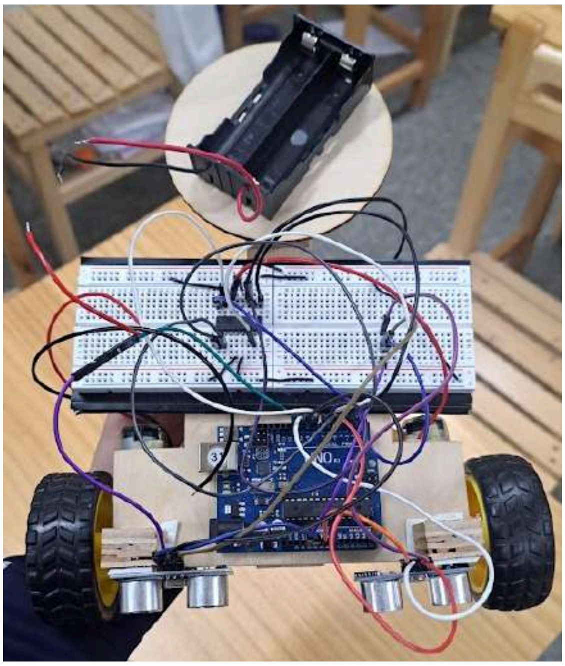
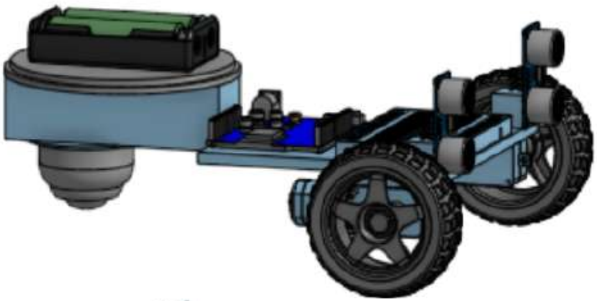
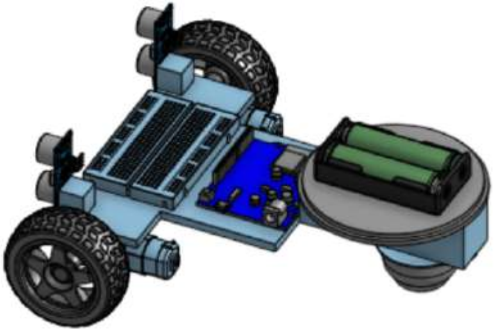
#259=CARTESIAN_POINT(’’,(1.983,0.,0.672));
#260=CARTESIAN_POINT(’’,(2.0635,0.,0.672));
#261=CARTESIAN_POINT(’’,(2.0635,0.,0.672));
#262=CARTESIAN_POINT(’’,(2.0635,0.,0.2225));
#263=CARTESIAN_POINT(’’,(2.0635,0.,0.2225));
#264=CARTESIAN_POINT(’’,(2.29658791853599,1.32818045626203E-17,0.209908015409663));
#265=(
GEOMETRIC_REPRESENTATION_CONTEXT(3)
GLOBAL_UNCERTAINTY_ASSIGNED_CONTEXT((#266))
GLOBAL_UNIT_ASSIGNED_CONTEXT((#269,#268,#267))
REPRESENTATION_CONTEXT(’HC-04ShapeString011’,’TOP_LEVEL_ASSEMBLY_PART’)
);
#266=UNCERTAINTY_MEASURE_WITH_UNIT(LENGTH_MEASURE(1.E-5),#269,
’DISTANCE_ACCURACY_VALUE’,’Maximum Tolerance applied to model’);
#267=(
NAMED_UNIT(*)
SI_UNIT($,.STERADIAN.)
SOLID_ANGLE_UNIT()
);
#268=(
NAMED_UNIT(*)
PLANE_ANGLE_UNIT()
SI_UNIT($,.RADIAN.)
);
#269=(
LENGTH_UNIT()
NAMED_UNIT(*)
SI_UNIT(.MILLI.,.METRE.)
);
#270=PRODUCT_DEFINITION_SHAPE(’’,’’,#271);
#271=PRODUCT_DEFINITION(’’,’’,#273,#272);
#272=PRODUCT_DEFINITION_CONTEXT(’’,#279,’design’);
#273=PRODUCT_DEFINITION_FORMATION_WITH_SPECIFIED_SOURCE(’’,’’,#275,
 .NOT_KNOWN.);
#274=PRODUCT_RELATED_PRODUCT_CATEGORY(’’,’’,(#275));
#275=PRODUCT(’HC-04ShapeString011’,’HC-04ShapeString011’,
’HC-04ShapeString011’,(#277));
#276=PRODUCT_CATEGORY(’’,’’);
#277=PRODUCT_CONTEXT(’’,#279,’mechanical’);
#278=APPLICATION_PROTOCOL_DEFINITION(’international standard’,
’ap242_managed_model_based_3d_engineering’,2011,#279);
#279=APPLICATION_CONTEXT(’managed model based 3d engineering’);
ENDSEC;
END-ISO-10303-21;
```

第四節　車體設計、電路配置與 Arduino 板實測

車體設計



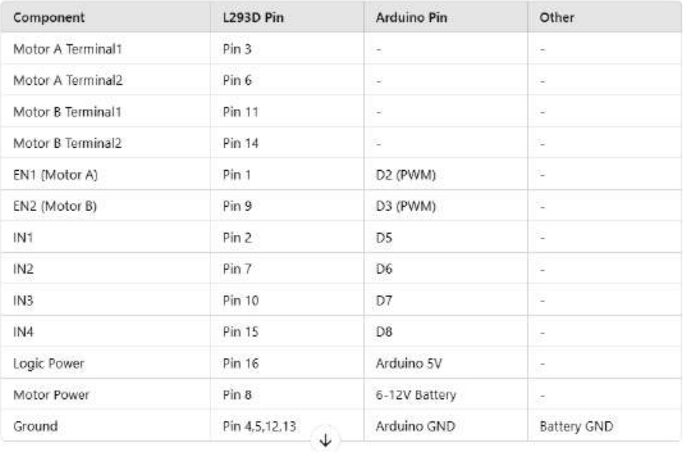




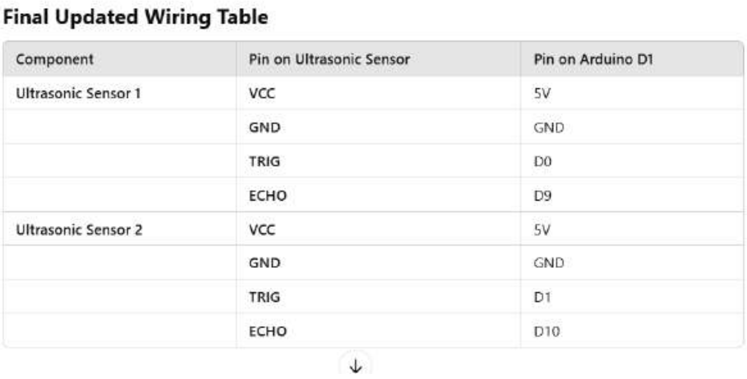
本車的車體設計為三輪車，由兩個前輪驅動，而後輪以萬向滾輪使其可以跟著前輪二馬達的轉速差而轉向，據說這樣前輪驅動的三輪車是比較省力(節能)的形式。車體底板由薄木板切割，形如釁，並且額外切割一片木板以加固；而後輪萬向滾輪部分以螺絲固定在厚木塊上，其上則有承載電池盒與行動電源(預想)的圓板。

零件部分，從前到後為超音波感測器、Arduino板、麵包板、電池盒與行動電源(實裝，建模時原本麵包板和Arduino板位置相反)。除了接線距離最短與空間安排剛好可以塞下以外，後面的萬向滾輪需要一定配重才能自由滾動(否則只能滑動)，因此電池盒和行動電源置於後方。

電路配置與接線



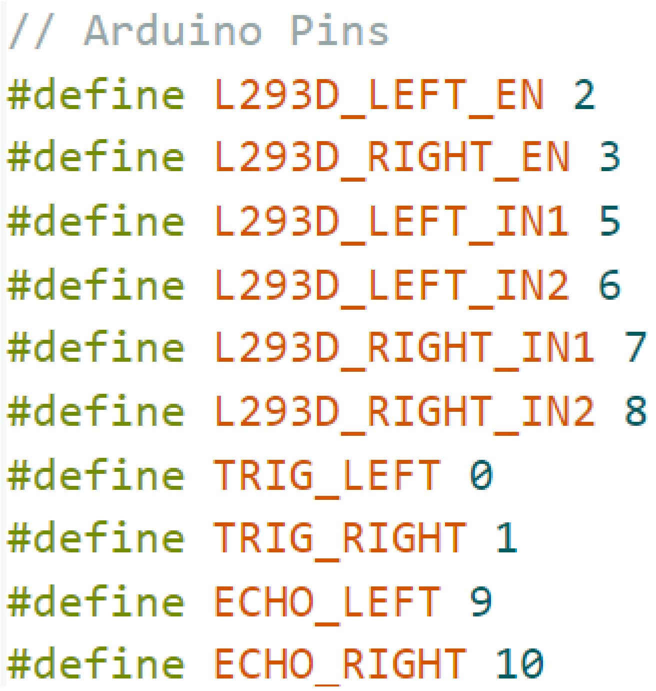
Component	L293D Pin	Arduino Pin	Other
Motor A Terminal1	Pin 3	-	-
Motor A Terminal2	Pin 6	-	-
Motor B Terminal1	Pin 11	-	-
Motor B Terminal2	Pin 14	-	-
EN1 (Motor A)	Pin 1	D2 (PWM)	-
EN2 (Motor B)	Pin 9	D3 (PWM)	-
IN1	Pin 2	D5	-
IN2	Pin 7	D6	-
IN3	Pin 10	D7	-
IN4	Pin 15	D8	-
Logic Power	Pin 16	Arduino 5V	-
Motor Power	Pin 8	6-12V Battery	-
Ground	Pin 4,5,12,13	Arduino GND	Battery GND



Final Updated Wiring Table

Component	Pin on Ultrasonic Sensor	Pin on Arduino D1
Ultrasonic Sensor 1	VCC	5V
	GND	GND
	TRIG	D0
	ECHO	D9
Ultrasonic Sensor 2	VCC	5V
	GND	GND
	TRIG	D1
	ECHO	D10

我們的電路配置與接線並沒有於tinkercad接出來，而是以gpt生成接線表格並檢查無誤後直接於麵包板與Arduino板接線。比較重要的部分在於L293D的各腳位接線，而在參考其他電路後也確認無誤(但有兩個腳位其實沒有使用到)。而程式碼的部分也依各腳位做修改。



```
// Arduino Pins
#define L293D_LEFT_EN 2
#define L293D_RIGHT_EN 3
#define L293D_LEFT_IN1 5
#define L293D_LEFT_IN2 6
#define L293D_RIGHT_IN1 7
#define L293D_RIGHT_IN2 8
#define TRIG_LEFT 0
#define TRIG_RIGHT 1
#define ECHO_LEFT 9
#define ECHO_RIGHT 10
```

Arduino D1 wifi板測試

D1板是ESP8266系列的板子之一，而我們其實並沒有使用其wifi的功能，而是做為普通Arduino板使用。然而，經過整整兩天的測試，程式依然無法上傳，因而放棄此方案。程式編譯成功，IDE裡板子的選擇也正確，然而一直遇到此問題：a fatal esptool.py error occurred: failed to connect to esp8266: timed out waiting for packet header

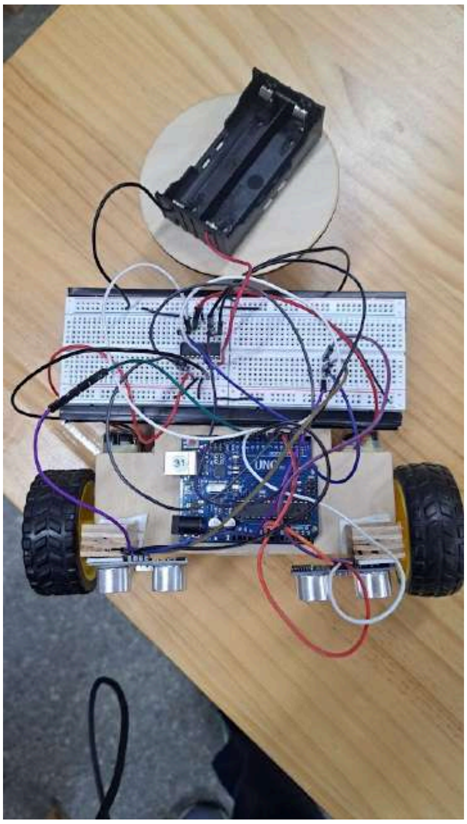
在經過查找相關網站、詢問GPT、寫簡單版本的程式嘗試燒錄並檢查所有可能的問題除錯之後，依然無法成功，可能是板子本身的問題也可能有其他問題。而以下為所有除錯，主要參考以下網站(當時沒有截圖)

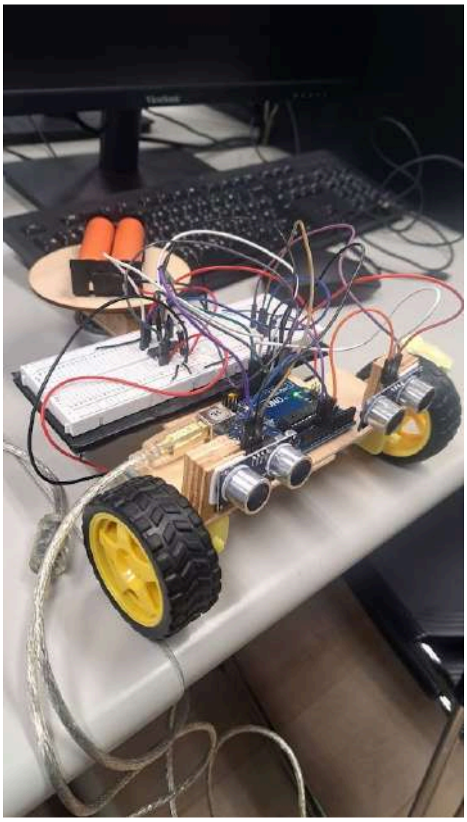
https://blog.csdn.net/weixin_65858849/article/details/131061031

1. 數據線問題：由於Arduino板上的燈有亮起，而在更早之前的測試也能燒錄，排除數據線問題的可能性
2. COM接口問題：於device manager確認Arduino裝置有在port被辨認到，而為了再次確認有卸載後再次安裝driver，確認此部分沒有問題
3. Baud率問題：於燒錄時已降低
4. 供壓不穩：以電腦接上應該無此問題
5. 串口被占用：後來將超音波偵測器的腳位都拔掉了
6. FLASH mode：這是最奇怪的部分，gpt與網站資料都說要將板子上的FLASH按鈕按下，於FLASH mode才能燒錄程式，然而再三確認後並沒有發現此按鈕(僅有RESET鍵)，可能是型號問題；而gpt給的建議是將GPIO0接至GND，而板子上也沒有標示為GPIO0的腳位，後來gpt說D1板的GPIO0為D3腳位，然而將其接至GND後也無法燒錄，最後在所有除錯皆確認並失敗之後改用UNO板。

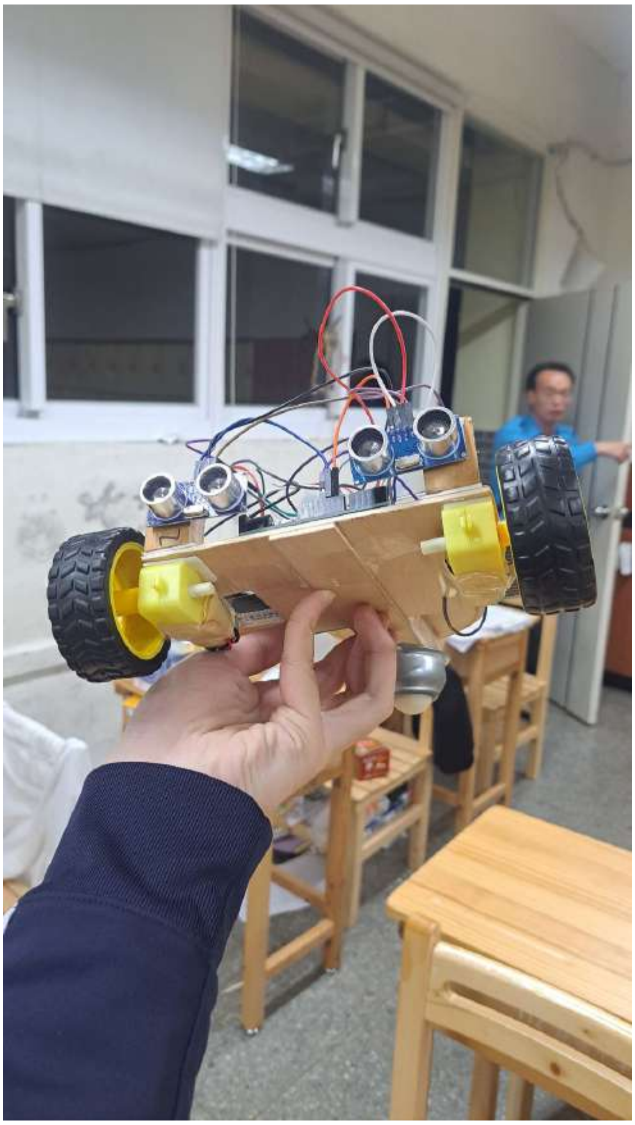
Arduino UNO R3板測試

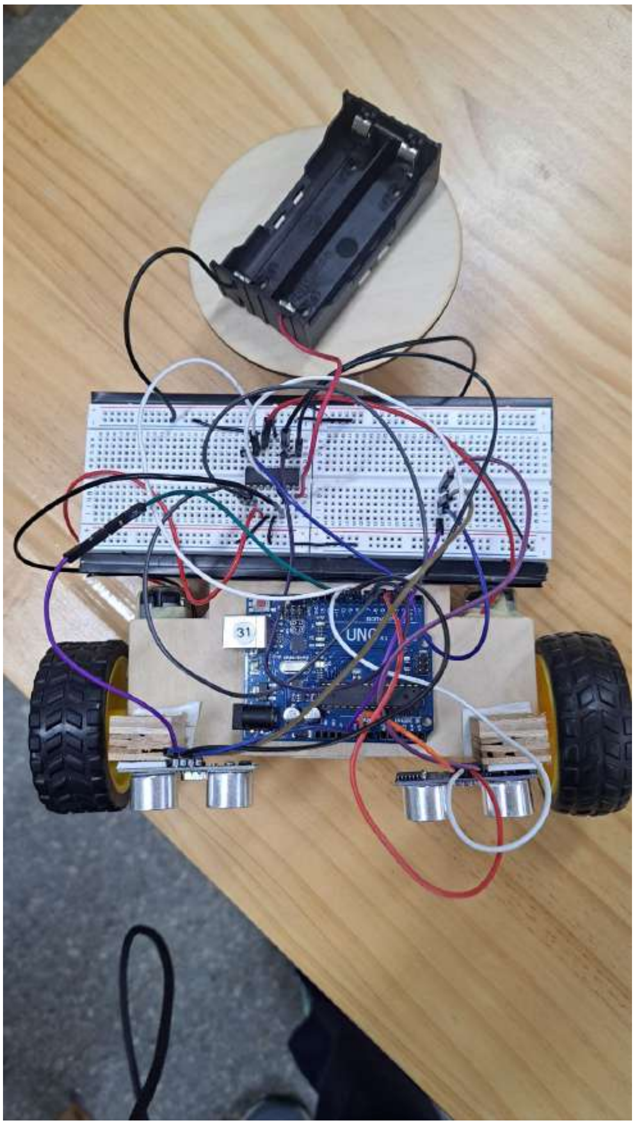
後來借到UNO板進行測試，電路以相同方式再次接線，唯一的不同是程式碼的腳位從D1等改成1。一開始燒錄依然出現問題，而查找資料後發現UNO板需要將0和1腳位的線拔掉才能燒錄，因為這是其通訊腳位。然而在燒錄成功後，超音波感測器有讀數了，在序列阜能看到超音波讀數與馬達輸出，然而馬達並沒有轉動，而以LED閃爍的測試程式上傳卻能成功運作。經過檢查接線都沒有問題，而懷疑可能是電池電壓不足或是馬達太鬆，然而充電後馬達依然沒有轉動。至此由於時間問題，已經無法再一步步除錯與測試，而就此打住了。

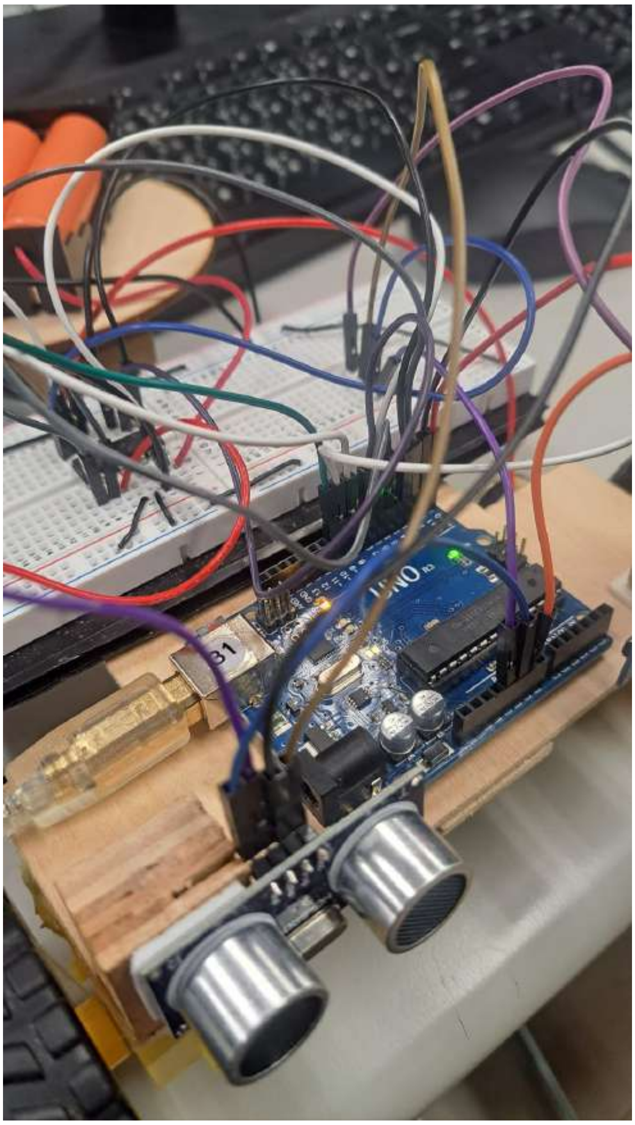


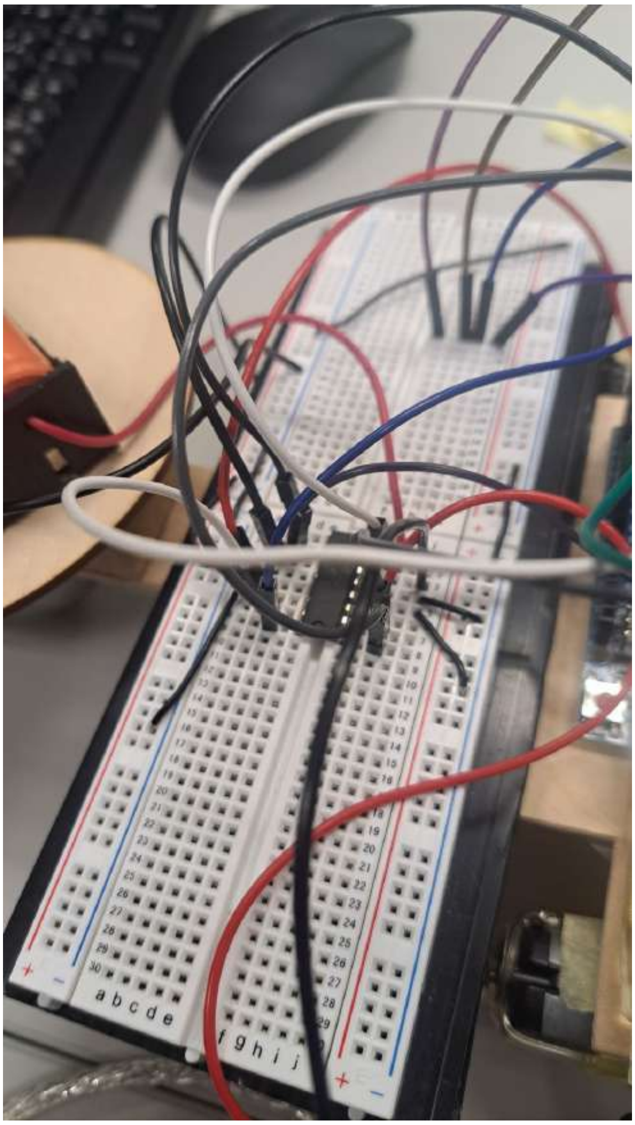


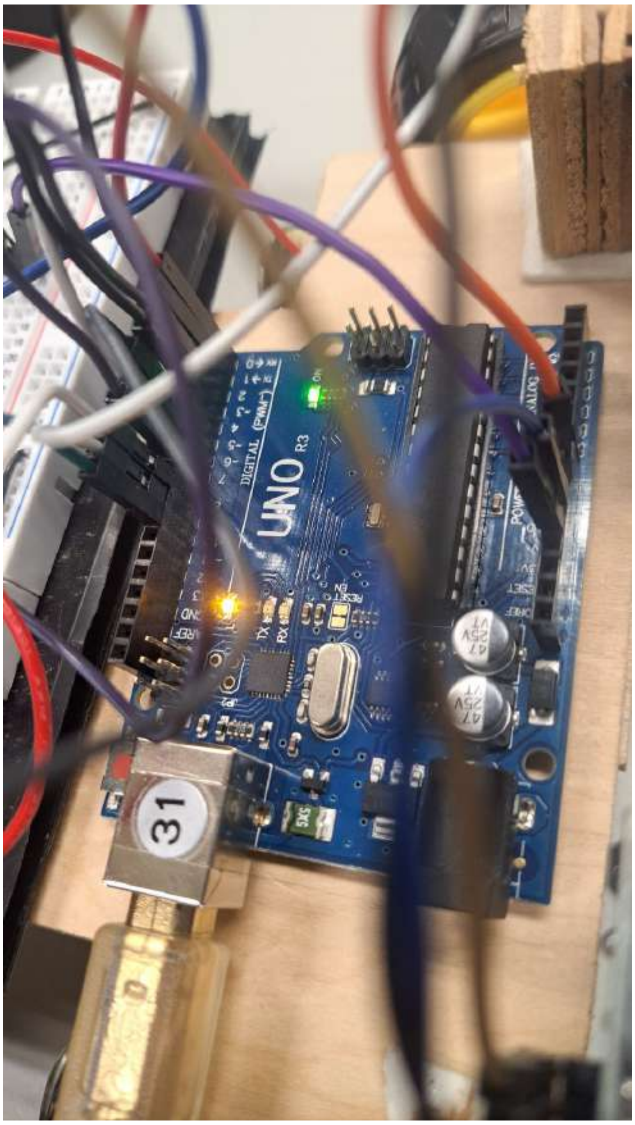
六、　零件與車體照片

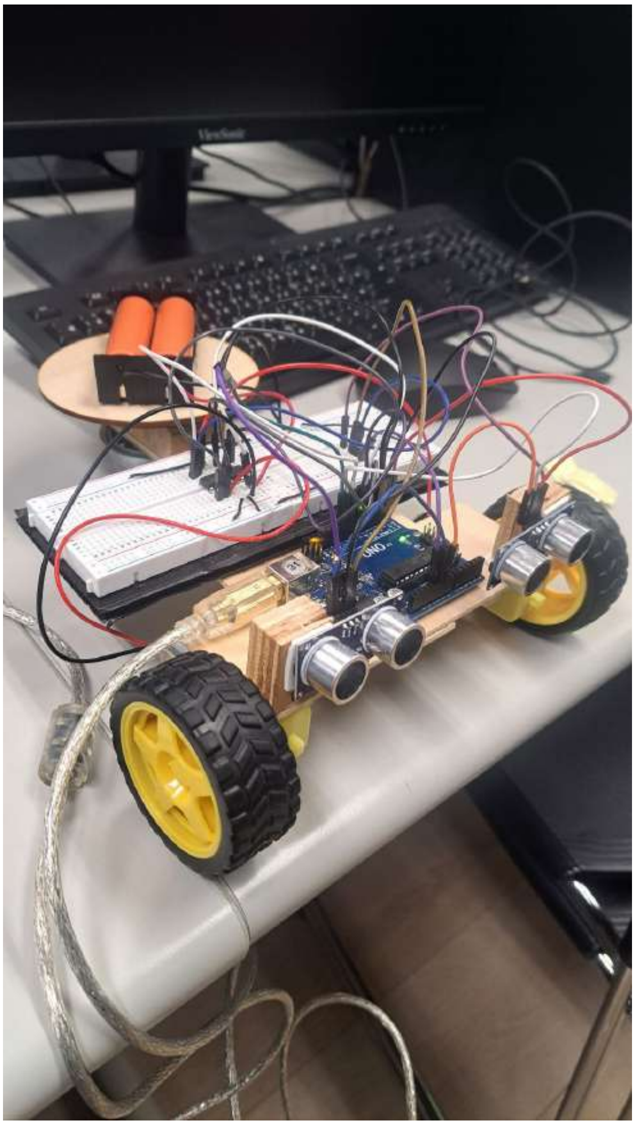



UNO
31









第五節　PID Controller, Software Simulation, Parameters Optimization, and Arduino Code

I implemented a PID (Proportional-Integral-Derivative) controller designed to regulate the speed of the auto-following kart with a leader robot. The implementation includes the PID controller logic, a car simulation, a framework for testing various PID configurations, and the Arduino applications.

一、　PID.hpp

This header file implements a PID controller that includes traditional PID control logic along with enhancements such as adaptive gain adjustment, adaptive integral term, error history management, and additional derivative term. It is also designed to be compatible with both Arduino and non-Arduino environments.

(一)　Code

```
#ifndef PID_HPP
#define PID_HPP

#ifdef ARDUINO
#include <Arduino.h>
#include <math.h>
#define to_string(a) String(a)
#else
#include <cmath>
#include <string>
#define String string
using namespace std;
#endif
#define MAX(a, b) (((a) > (b)) ? (a) : (b))
#define MIN(a, b) (((a) < (b)) ? (a) : (b))
#define ABS(a) ((a) < 0 ? -(a) : (a))
#define COPYSIGN(a, b) ((b) < 0 ? -ABS(a) : ABS(a))
#define CLAMP(a, b, c) (MAX(MIN((a), (b)), (c)))

struct Data {
    unsigned long dt;
    double e;
};

struct Node {
    Data data;
    Node* prev;
};

struct List {
    Node* head;
    Node* tail;
    unsigned int size;
};

class PID {
public:
    const double maxIntTm, maxAmp, minKp, maxKp, rTiM, TdM, TddM, eDPm, eDPa;
    const unsigned long session;
    double Kp, Ki, Kd, Kdd, preE, preDv, intg, preOut;
    unsigned long preT;
    List dtXs;

    PID(double maxIntTm, double maxAmp, double minKp, double maxKp, double rTiM, double TdM, double TddM,
        double eDPm, double eDPa, unsigned long session, double Kp, double preE=0, unsigned long preT=0)
        : maxIntTm(maxIntTm), maxAmp(maxAmp), minKp(minKp), maxKp(maxKp), rTiM(rTiM), TdM(TdM), TddM(TddM),
            eDPm(eDPm), eDPa(eDPa), session(session), Kp(Kp), Ki(0), Kd(0), Kdd(0), preE(preE), preDv(0),
            intg(0), preOut(0), preT(preT), dtXs({nullptr, nullptr, 0}) {}

    double update(double e, unsigned long timestamp, String* debug = nullptr) {
        unsigned long dt = timestamp - preT;
        preT = timestamp;

        if (dt == 0) {
            if (debug != nullptr) {
                *debug += ”dt=0\n”;
            }
            return preOut;
        }

        double amp, ap;

        if (session>0) {
            unsigned long S = 0;
            amp = 0;
            if (dtXs.size > 1) {
                Node* pos = dtXs.tail;
                while (dtXs.size > 1 && pos != nullptr) {
                    S += pos->data.dt;
                    amp = MAX(ABS(pos->data.e), amp);
                    if (S > session) {
                        dtXs.head = pos;
                        Node* cur = pos->prev;
                        pos->prev = nullptr;
                        while (cur != nullptr) {
                            Node* tmp = cur->prev;
                            delete cur;
                            cur = tmp;
                            dtXs.size--;
                        }
                        break;
                    } else pos = pos->prev;
                }
            } else if (dtXs.size == 1) {
                amp = ABS(dtXs.tail->data.e);
            }
            ap = exp(-amp / maxAmp);
        } else {
            amp=0;
            ap=1;
        }

        Ki = Kp * rTiM * ap;
        Kd = Kp * TdM * ap;
        Kdd = Kd * TddM;

        double dv = (e - preE) / dt;
        double dd = (dv - preDv) / dt;

        intg += e * dt;
        double intTm = Ki * intg;
        if (ABS(intTm) > maxIntTm) {
            intg = COPYSIGN(maxIntTm / Ki, intTm);
            intTm = COPYSIGN(maxIntTm, intTm);
        }

        double propTm = Kp * e;
        double dvTm = Kd * dv;
        double ddTm = Kdd * dd;
        double out = propTm + intTm + dvTm + ddTm;

        double eDP = e * dv;
        if (ABS(eDP) > eDPm) {
            Kp *= (eDP < 0) ? (1+eDPa) : (1-eDPa);
            Kp = MIN(MAX(Kp, minKp), maxKp);
        }

        if (debug != nullptr) {
            *debug += "update() called\ndt: " + to_string(dt) + ", e: " + to_string(e) + ", dv: " + to_string(dv) + ", dd: " + to_string(dd) +", amp: " + to_string(amp) +", ap: " + to_string(ap) + ",\nKp: " + to_string(Kp) + ", Ki: " + to_string(Ki) + ", Kd: " + to_string(Kd) + ", Kdd: " + to_string(Kdd) + ",\npropTm: " + to_string(propTm) + ", intTm: " + to_string(intTm) + ", dvTm: " + to_string(dvTm) + ", ddTm: " + to_string(ddTm) + ",\neDP: " + to_string(eDP) + ", out: " + to_string(out) + "\n";
        }

        preE = e;
        preDv = dv;
        preOut = out;

        if (session>0) {
            Node* nn = new Node{{dt, e}, dtXs.tail};
            dtXs.tail = nn;
            if (dtXs.size == 0) dtXs.head = nn;
            dtXs.size++;
       }

        return out;
    }
};

#endif
```

(二) Traditional PID Controller

The traditional PID controller is defined by the following equation:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\,\mathrm{d}\tau + K_d \frac{\mathrm{d}e(t)}{\mathrm{d}t},$$

where:

- $u(t)$ is the control output.
- $e(t)$ is the error at time t, defined as the difference between the desired value and the measured value.
- K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively.

(三) Adaptive Gain Adjustment

The proportional gain K_p is dynamically adjusted based on the interaction between the current error $e(t)$ and its rate of change (derivative). This adjustment is designed to improve the responsiveness of the controller to changing conditions. The adaptation can be mathematically expressed as follows:

$$K_p' = K_p \times (1 \pm eDP_a),$$

where:

- $eDP = e(t) \times \dfrac{de(t)}{dt}$
- eDP_m is a threshold that determines when to adjust the proportional gain.
- eDP_a is the adjustment factor that scales the change in K_p based on the error’ s derivative.

The key idea behind this adjustment is to increase the proportional gain when the system is experiencing a large error combined with a significant rate of change, which could indicate an approaching overshoot or oscillation. Conversely, if the error is decreasing but remains large, it may reduce the proportional gain to prevent excessive correction, allowing the system to stabilize more smoothly.

(四) Adaptive Integral Term

Integral control is essential for eliminating steady-state error; however, it can lead to issues like integral windup, where the integral term accumulates excessively during periods of sustained error. To mitigate this, the integral gain K_i is adaptively computed as follows:

$$K_i = K_p \times rTiM \times ap$$

Where:

- $ap = e^{-\frac{\text{amp}}{\text{maxAmp}}}$
- $rTiM$ is a constant that relates to the desired integral time constant.

The variable amp represents the maximum amplitude of error observed over a session. By using the exponential decay factor ap, the contribution of the integral term is diminished during periods of high error, effectively reducing the risk of windup. When the error is within an acceptable range, ap approaches 1, allowing the integral term to contribute effectively to the control output.

(五) Error History Management

Inspired by the **Ziegler–Nichols tuning method**, the implementation maintains a history of past errors and their timestamps to calculate the derivative and integral terms accurately. This history management is crucial for two main reasons:

- **Deriving the Rate of Change**: The derivative term requires knowledge of how fast the error is changing. By storing previous error values in a linked list, we can accurately compute the change in error over time ($\frac{de(t)}{dt}$):
$$dv = \frac{e(t) - preE}{dt}$$
- **Integral Calculation**: The integral of the error is accumulated over time, enabling the controller to respond to persistent deviations from the setpoint:
$$intg{+} = e(t) \times dt$$

Using a linked list allows for efficient management of this error history. As new errors are added, older entries can be pruned to ensure that only relevant data is retained, which helps avoid excessive memory usage and keeps the calculations focused on the most recent behavior of the system.

(六) Additional Derivative Term

In addition to the standard derivative term K_d, an additional derivative term K_{dd} is included in the PID controller. This term represents a second derivative component, which can be defined as follows:

$$K_{dd} = K_d \times TddM,$$

where $TddM$ is a multiplier that adjusts the impact of the second derivative term.
The inclusion of K_{dd} helps the controller anticipate changes in the error more effectively. By accounting for the acceleration of the error (i.e., how the rate of error change is itself changing), this additional term enhances the damping characteristics of the controller, allowing for more refined control responses, especially in systems that are subject to rapid changes or oscillations.

(七) Data Structures

- **Data**: Holds the time difference (`dt`) and error value (`e`).
- **Node**: Represents an element in the linked list, containing `Data` and a pointer to the previous node.
- **List**: Manages the linked list, holding pointers to the head and tail nodes and the size of the list.

(八) PID Class

The `PID` class encapsulates the PID control logic. It includes:

- **Member Variables:**
  - Control gains: K_p, K_i, K_d, K_{dd} (additional derivative term).
  - State variables: `preE`, `preDv`, `intg`, `preOut`, and `preT`, which store the previous error, derivative, integral term, last output, and last timestamp, respectively.
  - `dtXs`: An instance of `List` to maintain historical error data.
- **Constructor:** Initializes the PID parameters and state variables.
- **Update Method:**
  - Takes the current error and timestamp, computes the control output, and updates the internal state.
  - Implements logic for calculating the adaptive gains, managing error history, and generating the control signal.

二、 testCar.hpp

This header file includes a `Car` class for simulating the motion of a car, a PID controller for adjusting the speed of an auto-following kart based on the distance to a leader car, and several utility functions for data processing and results management.

(一) Code

```
#ifndef TESTCAR_HPP
#define TESTCAR_HPP

#include <iostream>
#include <cmath>
#include <string>
#include <vector>
#include <numeric>
#include <fstream>
#include <algorithm>
#include "PID.hpp"
using namespace std;

class Car
```

```
{
  public:
    Car(double initialSpeed, double initialPosition)
        : speed(initialSpeed), position(initialPosition) {}

    void updatePosition(double timeInterval)
    {
        position += speed * timeInterval;
    }

    void changeSpeed(double newSpeed)
    {
        speed = newSpeed;
    }

    double getPosition() const
    {
        return position;
    }

    double getSpeed() const
    {
        return speed;
    }

    double speed;
    double position;
};

void pidDebug(string message)
{
    cout << message;
}

double sum_last_squared(const std::vector<double> &v, double prop)
{
    if (v.empty())
        return 0.0;

    size_t n = v.size();
    size_t count = static_cast<size_t>(std::ceil(n * prop));
    size_t start_index = n - count;

    double sum_of_squares = std::accumulate(v.begin() + start_index, v.end(), 0.0,
                                            [](double sum, double value) {
                                                return sum + value * value;
                                            });
    return sum_of_squares;
}

vector<double> velocities(int steps)
{
    vector<double> velocities(steps, 0.0);
    double acceleration = 1;
    double error = 0.2;

    int phase_length = steps / 6;
    double velocity = 0.0;

    for (int i = 0; i < phase_length; ++i)
    {
        velocity += acceleration + ((i % 3 == 0) ? error : ((i % 3 == 1) ? (-error) : 0));
        velocities[i] = velocity;
    }

    for (int i = phase_length; i < 2 * phase_length; ++i)
    {
        velocity += ((i % 3 == 0) ? error : ((i % 3 == 1) ? (-error) : 0));
        velocities[i] = velocity;
    }

    for (int i = 2 * phase_length; i < 4 * phase_length; ++i)
    {
        velocity -= acceleration + ((i % 3 == 0) ? error : ((i % 3 == 1) ? (-error) : 0));
        velocities[i] = velocity;
    }

    for (int i = 4 * phase_length; i < 5 * phase_length; ++i)
    {
        velocity += acceleration + ((i % 3 == 0) ? error : ((i % 3 == 1) ? (-error) : 0));
        velocities[i] = velocity;
    }

    for (int i = 5 * phase_length; i < steps; ++i)
    {
        if (ABS(velocity) >= (error * (steps - i)))
        {
            velocity += COPYSIGN(velocity, error);
        }
        else
        {
            velocity += ((i % 3 == 0) ? error : ((i % 3 == 1) ? (-error) : 0));
        }
        velocities[i] = velocity;
    }

    return velocities;
}

vector<double> test(double maxIntTm, double maxAmp, double minKp, double maxKp, double rTiM, double TdM,
    double TddM, double eDPm, double eDPa, unsigned long session, double Kp, double preE = 0, unsigned long
    preT = 0, double timeInterval = 10, int steps = 50, bool debug = false)
{
    double leaderInitialSpeed = 0;
    double followerInitialSpeed = 0;
    double initialDistance = 0;

    vector<double> vec;
    vector<double> vol = velocities(steps);

    Car leader(leaderInitialSpeed, initialDistance);
    Car follower(followerInitialSpeed, 0);

    PID pid = PID(maxIntTm, maxAmp, minKp, maxKp, rTiM, TdM, TddM, eDPm, eDPa, session, Kp, preE, preT);

    cout << fixed << setprecision(4);

    for (int i = 0; i < steps; i++)
    {
        leader.changeSpeed(leader.getSpeed() + vol[i]);
        leader.updatePosition(timeInterval);
        follower.updatePosition(timeInterval);

        double distanceToLeader = leader.getPosition() - follower.getPosition();
        vec.push_back(distanceToLeader);
        string* ptr = nullptr;
        if (debug) {
            cout << "TimeStep: " << i << ", distanceToLeader: " << distanceToLeader << ", FollowerSpeed: " <<
                 follower.getSpeed() << ", LeaderSpeed: " << leader.getSpeed() << "\n";

            ptr = new string;
        }
        double fS = pid.update(distanceToLeader, i * timeInterval, ptr);
        follower.changeSpeed(follower.getSpeed() + MAX(-511, MIN(fS, 511)));
        if (debug) {
            cout << *ptr;
            delete ptr;
        }
    }

    return vec;
}

struct pidTest
{
    double maxIntTm, maxAmp, minKp, maxKp, rTiM, TdM, TddM, eDPm, eDPa;
    unsigned long session;
    double Kp, result;
};

bool write_results(const vector<pidTest> &data, const string &filename)
{
    auto sorted_data = data;
    sort(sorted_data.begin(), sorted_data.end(), [](const pidTest &a, const pidTest &b) {
        return a.result < b.result;
    });

    ofstream outfile(filename);
    if (!outfile)
    {
        cerr << ”Error opening file for writing.” << endl;
        return 0;
    }

    outfile << ”maxIntTm,maxAmp,minKp,maxKp,rTiM,TdM,TddM,eDPm,eDPa,session,Kp,result\n”;

    for (size_t i = 0; i < sorted_data.size(); ++i)
    {
        const pidTest &pt = sorted_data[i];
        outfile << pt.maxIntTm << ”,” << pt.maxAmp << ”,” << pt.minKp << ”,” << pt.maxKp << ”,”
                << pt.rTiM << ”,” << pt.TdM << ”,” << pt.TddM << ”,” << pt.eDPm << ”,” << pt.eDPa << ”,”
                << pt.session << ”,” << pt.Kp << ”,” << pt.result << ”\n”;
    }

    outfile.close();
    cout << ”Data written to ” << filename << endl;

    return 1;
}

struct ParameterRange
{
    double start;
    double end;
    double step;
};

#endif
```

(二) Car Class

The `Car` class represents a simple vehicle model with basic motion dynamics. It includes attributes for speed and position, as well as methods to update these attributes.

(三) PID Debugging Function

The `pidDebug` function is a utility for logging messages related to PID control operations.

(四) Sum of Last Squared Values

```
double sum_last_squared(const std::vector<double> &v, double prop)
```

Calculates the sum of squares of the last $n \times$ prop elements of the provided vector `v`.

(五) Velocity Generation

```
vector<double> velocities(int steps)
```

Generates a vector of velocity values over a specified number of simulation steps, simulating different phases of motion (acceleration, deceleration, and adjustments).

(六) PID Testing Function

```
vector<double> test(double maxIntTm, double maxAmp, double minKp, double maxKp, double rTiM, double TdM,
    double TddM, double eDPm, double eDPa, unsigned long session, double Kp, double preE = 0, unsigned long
    preT = 0, double timeInterval = 10, int steps = 1000)
```

This function simulates the interaction between a leader car and an auto-following kart using a PID controller to adjust the follower's speed based on the distance to the leader.

- **Parameters:**
  - `double maxIntTm`: Maximum integral time constant.
  - `double maxAmp`: Maximum amplitude of control output.
  - `double minKp`: Minimum proportional gain.
  - `double maxKp`: Maximum proportional gain.
  - `double rTiM`: Reference time interval multiplier.
  - `double TdM`: Derivative time multiplier.
  - `double TddM`: Second derivative time multiplier.
  - `double eDPm`: Maximum error derivative proportionality factor.
  - `double eDPa`: Error derivative adjustment factor.
  - `unsigned long session`: Session identifier for logging purposes.
  - `double Kp`: Initial proportional gain.
  - `double preE`: Previous error value (optional, defaults to 0).
  - `unsigned long preT`: Previous time value (optional, defaults to 0).
  - `double timeInterval`: Time interval for each step of simulation (default is 10).
  - `int steps`: Total number of simulation steps (default is 1000).
- **Returns:** A vector containing the distances between the leader and follower over time.

(七) PID Test Data Structure

```
struct pidTest
{
double maxIntTm, maxAmp, minKp, maxKp, rTiM, TdM, TddM, eDPm, eDPa;
unsigned long session;
double Kp, result;
};
```

The `pidTest` structure is used to store parameters for PID testing, along with the result of the simulation.

(八) Result Writing Function

```
bool write_results(const vector<pidTest> &data, const string &filename)
```

Writes the results of PID tests to a CSV file for analysis.

(九) ParameterRange

A structure to define the range of parameters for optimization.

- **Attributes:**
  - `double start`: The starting value of the parameter range.
  - `double end`: The ending value of the parameter range.
  - `double step`: The increment step for the parameter.

三、 optimization.hpp

This header file defines the optimization functions and structures used to optimize the parameters of a PID controller in a car simulation without multi-threaded processing.

(一) Code

```
#ifndef OPTIMIZATION_HPP
#define OPTIMIZATION_HPP

#include "testCar.hpp"
using namespace std;

int optimize(vector<ParameterRange> ranges)
{
    vector<pidTest> results;

    for (double maxIntTm = ranges[0].start; maxIntTm <= ranges[0].end; maxIntTm += ranges[0].step)
    {
        for (double maxAmp = ranges[1].start; maxAmp <= ranges[1].end; maxAmp += ranges[1].step)
        {
            for (double minKp = ranges[2].start; minKp <= ranges[2].end; minKp += ranges[2].step)
            {
                for (double maxKp = max(minKp, ranges[3].start);
                     maxKp <= ranges[3].end; maxKp += ranges[3].step)
                {
                    for (double rTiM = ranges[4].start; rTiM <= ranges[4].end; rTiM += ranges[4].step)
                    {
                        for (double TdM = ranges[5].start; TdM <= ranges[5].end; TdM += ranges[5].step)
                        {
                            for (double TddM = ranges[6].start; TddM <= ranges[6].end; TddM += ranges[6].step)
                            {
                                for (double eDPm = ranges[7].start; eDPm <= ranges[7].end; eDPm += ranges[7].step)
                                {
                                    for (double eDPa = ranges[8].start; eDPa <= ranges[8].end; eDPa += ranges[8].step)
                                    {
                                        for (unsigned long session = ranges[9].start; session <= ranges[9].end; session += ranges[9].step)
                                        {
                                            for (double Kp = MAX(minKp, ranges[10].start);
                                                 Kp <= MIN(maxKp, ranges[10].end); Kp += ranges[10].step)
                                            {
                                                vector<double> tmp = test(maxIntTm, maxAmp, minKp, maxKp, rTiM, TdM, TddM, eDPm, eDPa, session, Kp);
                                                double result = sum_last_squared(tmp, 0.5);
                                                results.push_back(pidTest({maxIntTm, maxAmp, minKp, maxKp, rTiM, TdM, TddM, eDPm, eDPa, session, Kp, result}));
                                            }
                                        }
                                    }
                                }
                            }
                        }
                    }
                }
            }
        }
    }

    if (!write_results(results, ”results.csv”))
    {
        cerr << ”Error writing results to file.” << endl;
        return EXIT_FAILURE;
    }

    return EXIT_SUCCESS;
}

#endif
```

(二) Optimize Function

Optimizes the parameters of the PID controller based on the provided ranges and writes results to a CSV file.

- **Parameters:**
  - `vector<ParameterRange> ranges`: A vector containing the ranges of parameters to optimize.
- **Returns:**
  - `int`: Returns `EXIT_SUCCESS` (0) if optimization completes successfully, otherwise returns `EXIT_FAILURE`.

四、 optimization_multithread.hpp

This header file defines the optimization functions and structures used to optimize the parameters of a PID controller in a car simulation with multi-threaded processing.

```cpp
#ifndef OPTIMIZATION_MULTITHREAD_HPP
#define OPTIMIZATION_MULTITHREAD_HPP

#include <vector>
#include <iostream>
#include <thread>
#include <mutex>
#include <queue>
#include <atomic>
#include <chrono>
#include <iomanip>
#include <condition_variable>
#include <cmath>
#include "testCar.hpp"
using namespace std;

mutex resultsMutex;
mutex queueMutex;
atomic<int> totalCombinations(0);
atomic<int> processedCombinations(0);
queue<vector<double>> parameterQueue;
condition_variable cv;

void displayProgress()
{
    while (true)
    {
        {
            lock_guard<mutex> lock(queueMutex);
            if (processedCombinations >= totalCombinations)
            {
                break;
            }
            cout << "\rProgress: " << processedCombinations << "/" << totalCombinations
                 << " (" << fixed << setprecision(2)
                 << (static_cast<double>(processedCombinations) / totalCombinations * 100)
                 << "%)          " << flush;
        }
        this_thread::sleep_for(chrono::seconds(1));
    }
    cout << "\rProgress: 100% Complete!                   " << endl;
}

size_t calculateSteps(const ParameterRange &range)
{
    return static_cast<size_t>(ceil((range.end - range.start) / range.step)) + 1;
}

void workerFunction(vector<pidTest> &results, atomic<bool> &running)
{
    while (running)
    {
        vector<double> params;

        {
            unique_lock<mutex> lock(queueMutex);
            cv.wait(lock, [] { return !parameterQueue.empty(); });
            if (parameterQueue.empty())
            {
                continue;
            }
            params = parameterQueue.front();
            parameterQueue.pop();
        }

        vector<double> tmp = test(
            params[0], params[1], params[2], params[3],
            params[4], params[5], params[6], params[7],
            params[8], params[9], params[10]);

        double result = sum_last_squared(tmp, 0.5);

        {
            lock_guard<mutex> lock(resultsMutex);
            results.emplace_back(pidTest{
                params[0], params[1], params[2], params[3],
                params[4], params[5], params[6], params[7],
                params[8], static_cast<unsigned long>(params[9]),
                params[10], result});
        }

        processedCombinations++;
        cv.notify_one();
    }
}

int optimize(vector<ParameterRange> ranges)
{
    totalCombinations = 1;
    for (const auto &range : ranges)
    {
        size_t steps = calculateSteps(range);
        if (totalCombinations > 0 && steps > SIZE_MAX / totalCombinations)
        {
            cerr << "Error: Too many combinations, would cause overflow" << endl;
            return 1;
        }
        totalCombinations = totalCombinations * steps;
    }

    cout << "Total parameter combinations to test: " << totalCombinations << endl;

    for (double maxIntTm = ranges[0].start; maxIntTm <= ranges[0].end; maxIntTm += ranges[0].step)
    {
        for (double maxAmp = ranges[1].start; maxAmp <= ranges[1].end; maxAmp += ranges[1].step)
        {
            for (double minKp = ranges[2].start; minKp <= ranges[2].end; minKp += ranges[2].step)
            {
                for (double maxKp = max(minKp, ranges[3].start);
                     maxKp <= ranges[3].end; maxKp += ranges[3].step)
                {
                    for (double rTiM = ranges[4].start; rTiM <= ranges[4].end; rTiM += ranges[4].step)
                    {
                        for (double TdM = ranges[5].start; TdM <= ranges[5].end; TdM += ranges[5].step)
                        {
                            for (double TddM = ranges[6].start; TddM <= ranges[6].end; TddM += ranges[6].step
                                )
                            {
                                for (double eDPm = ranges[7].start; eDPm <= ranges[7].end; eDPm += ranges[7].
                                    step)
                                {
                                    for (double eDPa = ranges[8].start; eDPa <= ranges[8].end; eDPa += ranges
                                        [8].step)
                                    {
                                        for (unsigned long session = ranges[9].start; session <= ranges[9].
                                            end; session += ranges[9].step)
                                        {
                                            for (double Kp = MAX(minKp, ranges[10].start);
                                                 Kp <= MIN(maxKp, ranges[10].end); Kp += ranges[10].step)
                                            {
                                                parameterQueue.push(pidTest({maxIntTm, maxAmp, minKp, maxKp,
                                                    rTiM, TdM, TddM, eDPm, eDPa, session, Kp}));
                                            }
                                        }
                                    }
                                }
                            }
                        }
                    }
                }
            }
        }
    }

    vector<pidTest> results;
    vector<thread> threads;
    atomic<bool> running(true);

    thread progressThread(displayProgress);
    unsigned int numThreads = thread::hardware_concurrency();
    cout << ”Using ” << numThreads << ” threads” << endl;

    for (unsigned int i = 0; i < numThreads; ++i)
    {
        threads.emplace_back(workerFunction, ref(results), ref(running));
    }

    for (auto &thread : threads)
    {
        thread.join();
    }

    running = false;
    cv.notify_all();

    progressThread.join();

    if (!write_results(results, ”results.csv”))
    {
        cerr << ”Error writing results to file.” << endl;
        return EXIT_FAILURE;
    }

    return EXIT_SUCCESS;
}

#endif
```

(一) Optimize Function

Optimizes the parameters of the PID controller based on the provided ranges and writes results to a CSV file.

- **Parameters:**
  - `vector<ParameterRange> ranges`: A vector containing the ranges of parameters to optimize.

- **Returns:**
  - int: Returns EXIT_SUCCESS (0) if optimization completes successfully, otherwise returns EXIT_FAILURE.

五、 main.cpp

The code file demonstrates the usage of the optimization.hpp (or optimization_multithread.hpp) header file to perform parameter optimization for a PID controller. It defines a set of parameter ranges and calls the optimize function to evaluate different combinations of parameters.

(一) Code

```
#include ”optimization.hpp” // or #include ”optimization_multithread.hpp”

int main() {
    // Note that steps can’t be zero
    vector<ParameterRange> ranges = {
        {461.9, 461.9, 1},    // maxIntTm
        {517.9, 517.9, 1},     // maxAmp
        {0.00265, 0.00265, 1},       // minKp
        {0.472, 0.472, 1},      // maxKp
        {1, 1, 1},       // rTiM
        {65.37, 65.37, 1},       // TdM
        {1.7, 1.7, 1},        // TddM
        {125, 125, 1}, // eDPm
        {0.15, 0.15, 1},    // eDPa
        {140, 140, 10},       // session
        {0.2436, 0.2436, 1}      // Kp
    };

    return optimize(ranges);
}
```

(二) Notes

Note that steps can’t be zero or the program won’t stop.

六、 main.ino

This Arduino code is for controlling a differential-drive robot using two ultrasonic sensors to measure distance, a PID (Proportional-Integral-Derivative) controller for speed and direction adjustments, and an L293D motor driver to control the motors based on sensor inputs.

(一) Code

```
// Arduino Pins
#define L293D_LEFT_EN 2
#define L293D_RIGHT_EN 3
#define L293D_LEFT_IN1 5
#define L293D_LEFT_IN2 6
#define L293D_RIGHT_IN1 7
#define L293D_RIGHT_IN2 8
```

```
#define TRIG_LEFT 4
#define TRIG_RIGHT 9
#define ECHO_LEFT 10
#define ECHO_RIGHT 11
// Constants
#define HALF_SOUND_SPEED 0.1715
#define TARGET_DISTANCE 15
#define DISTANCE_BETWEEN_ULTRASONIC_SENSORS 12
// Parameters to be tested
#define ANGULAR_SPEED_MULTIPLIER 0.8
#define LEFT_POSITIVE_SPEED_MULTIPLIER 1
#define LEFT_NEGATIVE_SPEED_MULTIPLIER 1.2
#define RIGHT_POSITIVE_SPEED_MULTIPLIER 1
#define RIGHT_NEGATIVE_SPEED_MULTIPLIER 1.2
// 1 for debug, 0 for not
#define DEBUG 1
// Adjust the above parameters
// The below code does not need to be changed

#include ”PID.hpp”

PID avgPID(461.9, 517.9, 0.00265, 0.472, 1, 65.37, 1.7, 125, 0.15, 140, 0.2436);
PID angPID(461.9, 517.9, 0.00265, 0.472, 1, 65.37, 1.7, 125, 0.15, 140, 0.2436);
double avgV;
double angV;
#if DEBUG
    String* ptr = new String();
#endif

inline double leftIn() {
    digitalWrite(TRIG_LEFT, LOW);
    delayMicroseconds(2);
    digitalWrite(TRIG_LEFT, HIGH);
    delayMicroseconds(10);
    digitalWrite(TRIG_LEFT, LOW);
    return pulseIn(ECHO_LEFT, HIGH) * HALF_SOUND_SPEED;
}

inline double rightIn() {
    digitalWrite(TRIG_RIGHT, LOW);
    delayMicroseconds(2);
    digitalWrite(TRIG_RIGHT, HIGH);
    delayMicroseconds(10);
    digitalWrite(TRIG_RIGHT, LOW);
    return pulseIn(ECHO_RIGHT, HIGH) * HALF_SOUND_SPEED;
}

void setup()
{
    Serial.begin (9600);
    pinMode(TRIG_LEFT, OUTPUT);
    pinMode(TRIG_RIGHT, OUTPUT);
    pinMode(ECHO_LEFT, INPUT);
    pinMode(ECHO_RIGHT, INPUT);
    pinMode(L293D_LEFT_IN1, OUTPUT);
    pinMode(L293D_LEFT_IN2, OUTPUT);
    pinMode(L293D_RIGHT_IN1, OUTPUT);
    pinMode(L293D_RIGHT_IN2, OUTPUT);
    avgV = 0;
    angV = 0;
}

void loop() {
    double left = leftIn();
    double right = rightIn();
    double avg = left + right;
    double ang = atan2(left - right, DISTANCE_BETWEEN_ULTRASONIC_SENSORS);

    #if DEBUG
        *ptr = ””;
        avgV += avgPID.update((avg - TARGET_DISTANCE), millis(), ptr);
        Serial.println(”Average Speed PID Update:”);
        Serial.println(*ptr);
        *ptr = ””;
        angV += angPID.update((ang - TARGET_DISTANCE), millis(), ptr) * ANGULAR_SPEED_MULTIPLIER;
        Serial.println(”Angular Speed Update:”);
        Serial.println(*ptr);
        *ptr = ””;
    #else
        avgV += avgPID.update((avg - TARGET_DISTANCE), millis());
        angV += angPID.update((ang - TARGET_DISTANCE), millis()) * ANGULAR_SPEED_MULTIPLIER;
    #endif

    double leftV = avgV + angV;
    double rightV = avgV - angV;

    leftOut(leftV);
    rightOut(rightV);

    delayMicroseconds(10000);
}

inline void leftOut(double leftV) {
    #if DEBUG
        Serial.println(”Left Original Velocity: ” + String(leftV));
    #endif
    leftV *= (leftV < 0)?LEFT_NEGATIVE_SPEED_MULTIPLIER:LEFT_POSITIVE_SPEED_MULTIPLIER;
    leftV = CLAMP(leftV, 255, -255);
    #if DEBUG
        Serial.println(”Left Outputted Velocity: ” + String(leftV));
    #endif
    if (leftV > 0) {
        analogWrite(L293D_LEFT_IN1, 0);
        analogWrite(L293D_LEFT_IN2, leftV);
    } else {
        analogWrite(L293D_LEFT_IN1, -leftV);
        analogWrite(L293D_LEFT_IN2, 0);
    }
}

inline void rightOut(double rightV) {
    #if DEBUG
        Serial.println(”Right Original Velocity: ” + String(rightV));
    #endif
    rightV *= (rightV < 0)?RIGHT_NEGATIVE_SPEED_MULTIPLIER:RIGHT_POSITIVE_SPEED_MULTIPLIER;
    rightV = CLAMP(rightV, 255, -255);
    #if DEBUG
        Serial.println(”Right Outputted Velocity: ” + String(rightV));
    #endif
    if (rightV > 0) {
        analogWrite(L293D_RIGHT_IN1, 0);
        analogWrite(L293D_RIGHT_IN2, rightV);
    } else {
        analogWrite(L293D_RIGHT_IN1, -rightV);
        analogWrite(L293D_RIGHT_IN2, 0);
    }
}
```

(二) Pin Definitions

- **L293D motor control pins:**
  - L293D_LEFT_EN and L293D_RIGHT_EN: Enable pins for the left and right motors.
  - L293D_LEFT_IN1, L293D_LEFT_IN2, L293D_RIGHT_IN1, L293D_RIGHT_IN2: Input pins for controlling the direction of the motors.
- **Ultrasonic sensor pins:**
  - TRIG_LEFT and TRIG_RIGHT: Trigger pins for the left and right ultrasonic sensors.
  - ECHO_LEFT and ECHO_RIGHT: Echo pins for the left and right ultrasonic sensors that return the duration of the reflected sound wave.

(三) Constants

- **HALF_SOUND_SPEED**: Constant used to convert the echo time into a distance. The value 0.1715 is derived from the speed of sound.
- **TARGET_DISTANCE**: The target distance that the robot should maintain between the two sensors (in centimeters).
- **DISTANCE_BETWEEN_ULTRASONIC_SENSORS**: The distance between the two ultrasonic sensors mounted on the robot, which is used to calculate angular adjustments.

(四) PID Tuning Parameters

- **PID Controllers (avgPID and angPID)**: Two PID controllers are used:
  - avgPID: Controls the average speed to keep the robot at the target distance.
  - angPID: Controls the angular speed to maintain proper alignment based on the sensor readings.

  The values provided for the PID controllers (like 461.9, 517.9, etc.) are the tuning parameters for each PID term (P, I, D).

(五) Functions and Code Flow

- **leftIn() and rightIn()**: These inline functions trigger the ultrasonic sensors by sending a pulse and measuring the time it takes for the sound to return. The return time is converted into a distance using the formula:

  $$\text{distance} = \frac{\text{time} \times \text{speed of sound}}{2}$$

  The resulting distance is then returned.
- **setup()**: This function runs once when the program starts. It initializes serial communication, sets pin modes for the motor control and ultrasonic sensors, and initializes the velocity variables (avgV and angV).

- **`loop()`**: This function runs repeatedly. It does the following:

  1. Reads the distance from the left and right ultrasonic sensors using `leftIn()` and `rightIn()`.
  2. Calculates the average distance (`avg`) and the angular difference (`ang`) between the two sensors.
  3. Applies the PID controllers to adjust the average speed and angular speed to maintain the target distance.
  4. Sets the left and right velocities (`leftV` and `rightV`) based on the PID updates and applies any necessary adjustments to control the motors.
  5. Sends the control signals to the motors using `leftOut()` and `rightOut()`.

(六) Motor Control (`leftOut()` and `rightOut()`)

- `leftOut()` and `rightOut()`: These inline functions are responsible for sending control signals to the motor driver (L293D). The functions adjust the speed based on the calculated velocity and apply any speed multipliers to tune motor behavior. The `analogWrite()` function is used to set the motor speeds, where:
  - Positive velocities drive the motors forward.
  - Negative velocities drive the motors backward.

(七) Debugging

If `DEBUG` is set to 1, additional information about the PID updates and motor velocities is printed to the serial monitor for troubleshooting and performance analysis.

七、 all.ino

Combining `PID.hpp` and `main.ino` in one file.

(一) Code

```
// Arduino Pins
#define L293D_LEFT_EN 2
#define L293D_RIGHT_EN 3
#define L293D_LEFT_IN1 5
#define L293D_LEFT_IN2 6
#define L293D_RIGHT_IN1 7
#define L293D_RIGHT_IN2 8
#define TRIG_LEFT 4
#define TRIG_RIGHT 9
#define ECHO_LEFT 10
#define ECHO_RIGHT 11
// Constants
#define HALF_SOUND_SPEED 0.1715
#define TARGET_DISTANCE 15
#define DISTANCE_BETWEEN_ULTRASONIC_SENSORS 12
// Parameters to be tested
#define ANGULAR_SPEED_MULTIPLIER 0.8
#define LEFT_POSITIVE_SPEED_MULTIPLIER 1
```

```
#define LEFT_NEGATIVE_SPEED_MULTIPLIER 1.2
#define RIGHT_POSITIVE_SPEED_MULTIPLIER 1
#define RIGHT_NEGATIVE_SPEED_MULTIPLIER 1.2
// 1 for debug, 0 for not
#define DEBUG 1
// Adjust the above parameters
// The below code does not need to be changed

#ifdef ARDUINO
#include <Arduino.h>
#include <math.h>
#define to_string(a) String(a)
#else
#include <cmath>
#include <string>
#define String string
using namespace std;
#endif
#define MAX(a, b) (((a) > (b)) ? (a) : (b))
#define MIN(a, b) (((a) < (b)) ? (a) : (b))
#define ABS(a) ((a) < 0 ? -(a) : (a))
#define COPYSIGN(a, b) ((b) < 0 ? -ABS(a) : ABS(a))
#define CLAMP(a, b, c) (MAX(MIN((a), (b)), (c)))

struct Data {
    unsigned long dt;
    double e;
};

struct Node {
    Data data;
    Node* prev;
};

struct List {
    Node* head;
    Node* tail;
    unsigned int size;
};

class PID {
public:
    const double maxIntTm, maxAmp, minKp, maxKp, rTiM, TdM, TddM, eDPm, eDPa;
    const unsigned long session;
    double Kp, Ki, Kd, Kdd, preE, preDv, intg, preOut;
    unsigned long preT;
    List dtXs;

    PID(double maxIntTm, double maxAmp, double minKp, double maxKp, double rTiM, double TdM, double TddM,
        double eDPm, double eDPa, unsigned long session, double Kp, double preE=0, unsigned long preT=0)
        : maxIntTm(maxIntTm), maxAmp(maxAmp), minKp(minKp), maxKp(maxKp), rTiM(rTiM), TdM(TdM), TddM(TddM),
            eDPm(eDPm), eDPa(eDPa), session(session), Kp(Kp), Ki(0), Kd(0), Kdd(0), preE(preE), preDv(0),
            intg(0), preOut(0), preT(preT), dtXs({nullptr, nullptr, 0}) {}

    double update(double e, unsigned long timestamp, String* debug = nullptr) {
        unsigned long dt = timestamp - preT;
        preT = timestamp;

        if (dt == 0) {
            if (debug != nullptr) {
                *debug += ”dt=0\n”;
            }
            return preOut;
        }

        double amp, ap;

        if (session>0) {
            unsigned long S = 0;
            amp = 0;
            if (dtXs.size > 1) {
                Node* pos = dtXs.tail;
                while (dtXs.size > 1 && pos != nullptr) {
                    S += pos->data.dt;
                    amp = MAX(ABS(pos->data.e), amp);
                    if (S > session) {
                        dtXs.head = pos;
                        Node* cur = pos->prev;
                        pos->prev = nullptr;
                        while (cur != nullptr) {
                            Node* tmp = cur->prev;
                            delete cur;
                            cur = tmp;
                            dtXs.size--;
                        }
                        break;
                    } else pos = pos->prev;
                }
            } else if (dtXs.size == 1) {
                amp = ABS(dtXs.tail->data.e);
            }
            ap = exp(-amp / maxAmp);
        } else {
            amp=0;
            ap=1;
        }

        Ki = Kp * rTiM * ap;
        Kd = Kp * TdM * ap;
        Kdd = Kd * TddM;

        double dv = (e - preE) / dt;
        double dd = (dv - preDv) / dt;

        intg += e * dt;
        double intTm = Ki * intg;
        if (ABS(intTm) > maxIntTm) {
            intg = COPYSIGN(maxIntTm / Ki, intTm);
            intTm = COPYSIGN(maxIntTm, intTm);
        }

        double propTm = Kp * e;
        double dvTm = Kd * dv;
        double ddTm = Kdd * dd;
        double out = propTm + intTm + dvTm + ddTm;

        double eDP = e * dv;
        if (ABS(eDP) > eDPm) {
            Kp *= (eDP < 0) ? (1+eDPa) : (1-eDPa);
            Kp = MIN(MAX(Kp, minKp), maxKp);
        }

        if (debug != nullptr) {
            *debug += "update() called\ndt: " + to_string(dt) + ", e: " + to_string(e) + ", dv: " + to_string
                (dv) + ", dd: " + to_string(dd) +", amp: " + to_string(amp) +", ap: " + to_string(ap) + ",\
                nKp: " + to_string(Kp) + ", Ki: " + to_string(Ki) + ", Kd: " + to_string(Kd) + ", Kdd: " +
                to_string(Kdd) + ",\npropTm: " + to_string(propTm) + ", intTm: " + to_string(intTm) + ", dvTm
                : " + to_string(dvTm) + ", ddTm: " + to_string(ddTm) + ",\neDP: " + to_string(eDP) + ", out:
                " + to_string(out) + "\n";
        }

        preE = e;
        preDv = dv;
        preOut = out;

        if (session>0) {
            Node* nn = new Node{{dt, e}, dtXs.tail};
            dtXs.tail = nn;
            if (dtXs.size == 0) dtXs.head = nn;
            dtXs.size++;
       }

        return out;
    }
};

PID avgPID(461.9, 517.9, 0.00265, 0.472, 1, 65.37, 1.7, 125, 0.15, 140, 0.2436);
PID angPID(461.9, 517.9, 0.00265, 0.472, 1, 65.37, 1.7, 125, 0.15, 140, 0.2436);
double avgV;
double angV;
#if DEBUG
    String* ptr = new String();
#endif

inline double leftIn() {
    digitalWrite(TRIG_LEFT, LOW);
    delayMicroseconds(2);
    digitalWrite(TRIG_LEFT, HIGH);
    delayMicroseconds(10);
    digitalWrite(TRIG_LEFT, LOW);
    return pulseIn(ECHO_LEFT, HIGH) * HALF_SOUND_SPEED;
}

inline double rightIn() {
    digitalWrite(TRIG_RIGHT, LOW);
    delayMicroseconds(2);
    digitalWrite(TRIG_RIGHT, HIGH);
    delayMicroseconds(10);
    digitalWrite(TRIG_RIGHT, LOW);
    return pulseIn(ECHO_RIGHT, HIGH) * HALF_SOUND_SPEED;
}

void setup()
{
    Serial.begin (9600);
    pinMode(TRIG_LEFT, OUTPUT);
    pinMode(TRIG_RIGHT, OUTPUT);
    pinMode(ECHO_LEFT, INPUT);
    pinMode(ECHO_RIGHT, INPUT);
    pinMode(L293D_LEFT_IN1, OUTPUT);
    pinMode(L293D_LEFT_IN2, OUTPUT);
    pinMode(L293D_RIGHT_IN1, OUTPUT);
    pinMode(L293D_RIGHT_IN2, OUTPUT);
    avgV = 0;
    angV = 0;
}

void loop() {
    double left = leftIn();
    double right = rightIn();
    double avg = left + right;
    double ang = atan2(left - right, DISTANCE_BETWEEN_ULTRASONIC_SENSORS);

    #if DEBUG
        *ptr = "";
        avgV += avgPID.update((avg - TARGET_DISTANCE), millis(), ptr);
        Serial.println(”Average Speed PID Update:”);
        Serial.println(*ptr);
        *ptr = ””;
        angV += angPID.update((ang - TARGET_DISTANCE), millis(), ptr) * ANGULAR_SPEED_MULTIPLIER;
        Serial.println(”Angular Speed Update:”);
        Serial.println(*ptr);
        *ptr = ””;
    #else
        avgV += avgPID.update((avg - TARGET_DISTANCE), millis());
        angV += angPID.update((ang - TARGET_DISTANCE), millis()) * ANGULAR_SPEED_MULTIPLIER;
    #endif

    double leftV = avgV + angV;
    double rightV = avgV - angV;

    leftOut(leftV);
    rightOut(rightV);

    delayMicroseconds(10000);
}

inline void leftOut(double leftV) {
    #if DEBUG
        Serial.println(”Left Original Velocity: ” + String(leftV));
    #endif
    leftV *= (leftV < 0)?LEFT_NEGATIVE_SPEED_MULTIPLIER:LEFT_POSITIVE_SPEED_MULTIPLIER;
    leftV = CLAMP(leftV, 255, -255);
    #if DEBUG
        Serial.println(”Left Outputted Velocity: ” + String(leftV));
    #endif
    if (leftV > 0) {
        analogWrite(L293D_LEFT_IN1, 0);
        analogWrite(L293D_LEFT_IN2, leftV);
    } else {
        analogWrite(L293D_LEFT_IN1, -leftV);
        analogWrite(L293D_LEFT_IN2, 0);
    }
}

inline void rightOut(double rightV) {
    #if DEBUG
        Serial.println(”Right Original Velocity: ” + String(rightV));
    #endif
    rightV *= (rightV < 0)?RIGHT_NEGATIVE_SPEED_MULTIPLIER:RIGHT_POSITIVE_SPEED_MULTIPLIER;
    rightV = CLAMP(rightV, 255, -255);
    #if DEBUG
        Serial.println(”Right Outputted Velocity: ” + String(rightV));
    #endif
    if (rightV > 0) {
        analogWrite(L293D_RIGHT_IN1, 0);
        analogWrite(L293D_RIGHT_IN2, rightV);
    } else {
        analogWrite(L293D_RIGHT_IN1, -rightV);
        analogWrite(L293D_RIGHT_IN2, 0);
    }
}
```

八、 Development History

The development of this PID (Proportional-Integral-Derivative) controller project is rooted in control theory, a field of engineering that focuses on the behavior of dynamic systems. What makes us take the initiative is the auto-following kart lesson in our living technology class. We aim to make an auto-following kart from scratch with Arduino and wooden boards and make it as quality as possible on a constrained budget.

(一) Control Theory and PID Controllers

The development of this PID (Proportional-Integral-Derivative) controller project is rooted in control theory, a field of engineering that focuses on the behavior of dynamic systems. PID controllers are a cornerstone of modern control systems. They are designed to automatically adjust system outputs based on feedback to minimize error, allowing for precise control of dynamic systems. The PID controller operates based on three fundamental components:

- **Proportional Control (P)**: Responds proportionally to the current error value, providing immediate correction based on how far the system is from the desired state.
- **Integral Control (I)**: Addresses accumulated past errors, ensuring that the system reaches the desired state even if there are persistent biases.
- **Derivative Control (D)**: Predicts future errors based on the rate of change of the error, providing a damping effect to reduce overshoot and oscillation.

The tuning of these parameters is crucial for achieving optimal performance. The traditional Ziegler–Nichols tuning method has served as a foundational approach for many engineers, providing empirical guidelines for setting PID parameters based on system behavior.

(二) Development Tools

Balancing heavy academic responsibilities, including preparation for the GSAT, I primarily developed the advanced PID controller, simulation framework, and Arduino implementation using Linux emulation environments on my Android phone. This allowed me to utilize commuting time efficiently and maximize productivity during otherwise idle periods.

Leveraging my research on Android tools, such as **Android Non Root** (https://github.com/Willie169/Android-Non-Root) and **Termux Sh** (https://github.com/Willie169/termux-sh), I set up isolated Linux virtual environments on Termux to streamline my development process. A Debian Bookworm ARM64 proot environment served as the primary development platform due to its optimal performance and lightweight setup, a Debian Bookworm AMD64 QEMU system emulation installed for testing in a more realistic, computer-like environment, and an Alpine 3.21 Virt AMD64 QEMU system emulation configured for running Docker containers cloned from GitHub and GitLab repositories.

During development, I employed a suite of powerful and versatile tools. I primarily used `Vim` for editing to enhance coding speed and convenience, `G++` and `GCC` for compilation to run C and C++ programs, `GDB` for debugging to identify and resolve complex issues, and `git` for versioning to ensure my work remained organized, traceable, and collaborative-ready. These tools not only facilitated seamless development but also prepared me to adopt professional practices in future large-scale projects.

(三) Initial Implementation

The journey began with a simple implementation of the traditional PID controller. The focus was on creating a basic class structure in C++ that encapsulated the PID logic, allowing for straightforward application in simulations.

- **Key Features**:
  - Basic PID calculations.
  - Initial support for both Arduino and non-Arduino environments through conditional compilation.

(四) Enhancements and Adaptive Features

As the initial implementation was tested, several limitations became apparent, particularly regarding responsiveness and stability. This prompted the incorporation of advanced features such as:

- **Adaptive Gain Adjustment**: Inspired by the need for dynamic responsiveness, the proportional gain K_p was made adaptable based on the error's rate of change. This enhancement allowed for better handling of transient behaviors in the system.
- **Adaptive Integral Term**: To mitigate integral windup, the integral gain K_i was adjusted based on observed error amplitude. This feature improved system stability during sustained error conditions.

(五) Error History Management

To accurately compute the integral and derivative terms, a robust error history management system was implemented. This system utilized a linked list structure to store past error values and timestamps, enabling precise calculations for both the integral and derivative components. The integration of error history management was crucial for implementing more advanced tuning strategies, inspired by established control theory practices.

(六) Additional Derivative Term

Recognizing the need for improved damping characteristics, an additional derivative term K_{dd} was introduced. This term accounted for the acceleration of error changes, allowing the controller to anticipate and react to rapid fluctuations more effectively.

(七) Testing and Simulation Framework

With the PID logic in place, attention turned to building a comprehensive simulation framework to test various PID configurations. The introduction of the `Car` class for simulating follower and leader vehicles added a practical context for evaluating PID performance in a dynamic environment.

- **PID Testing Function**: A dedicated function was developed to simulate the interaction between the leader and follower karts, providing insights into how different PID parameters affected system behavior.

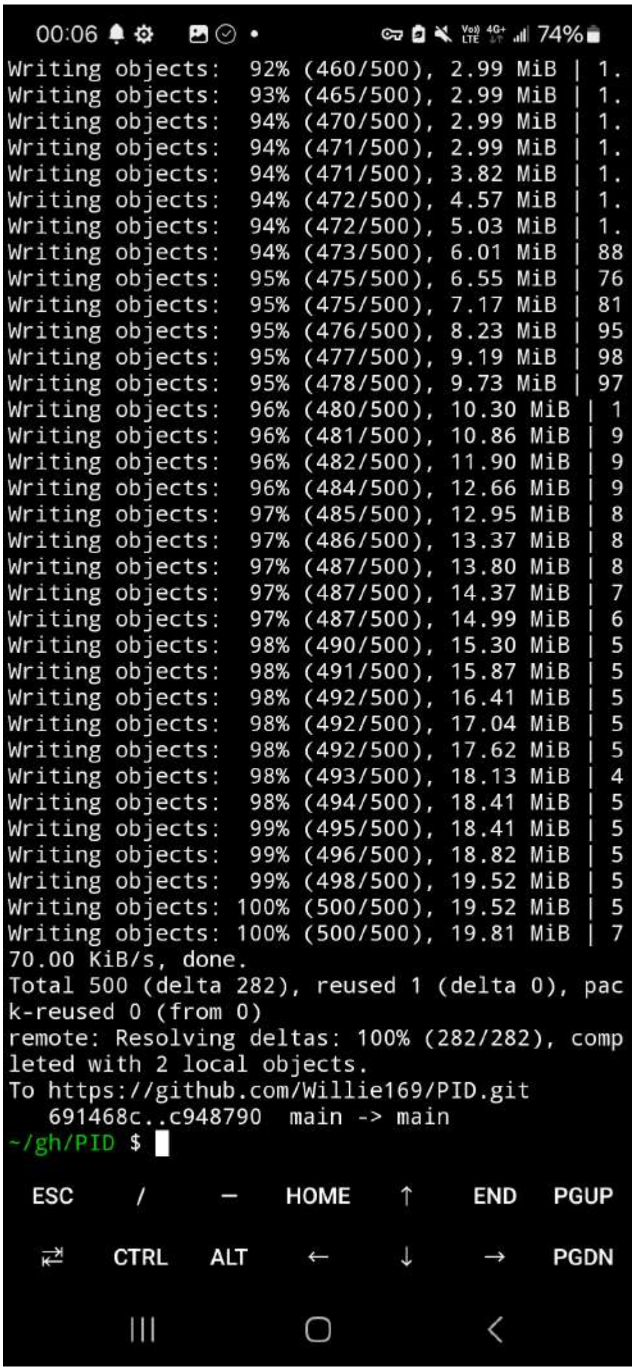
(八) Optimization and Multi-threading

To facilitate further exploration of PID parameter tuning, optimization functions were integrated. Utilizing multi-threading allowed for the concurrent evaluation of multiple parameter combinations, greatly enhancing the testing efficiency. The optimization framework also included mechanisms for result logging and progress tracking, making it easier to analyze and visualize outcomes.

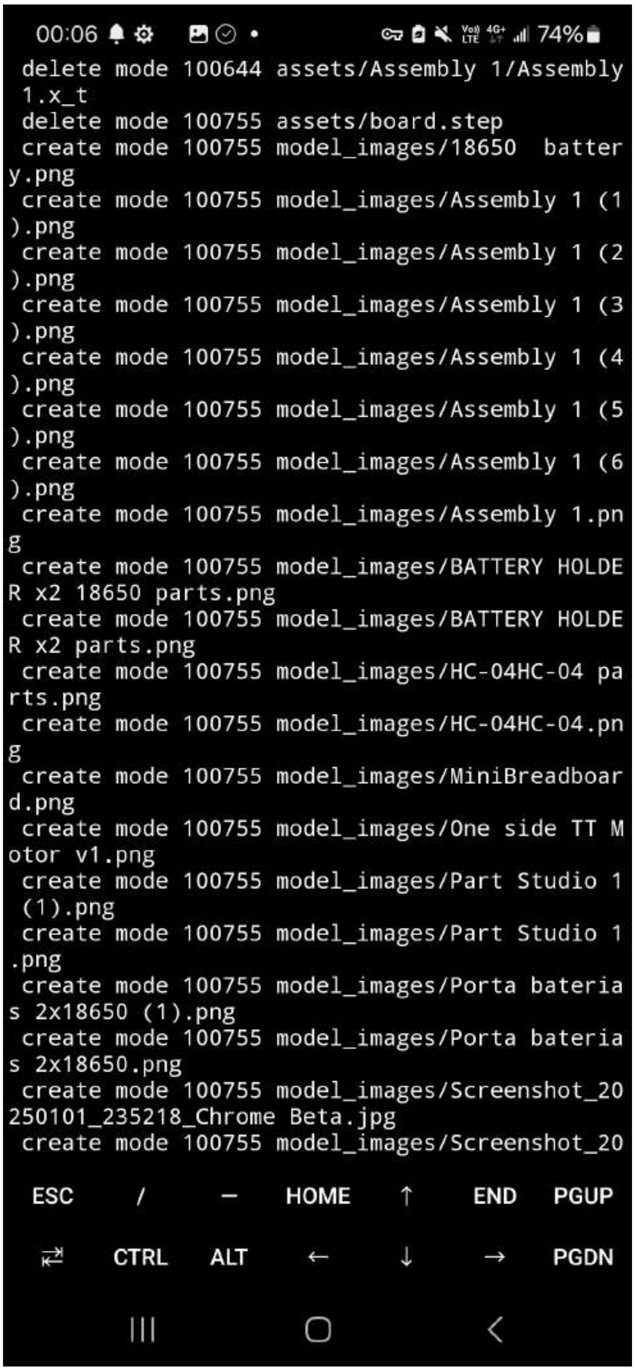
(九) Arduino Auto-Following Kart

We use two ultrasonic sensors to measure the distance on both sides. The difference in distance helps adjust the robot's angular velocity, while the average of both distances adjusts its linear speed. The PID controllers fine-tune these adjustments to ensure the robot stays at the target distance, while adjusting its orientation to keep the two sensors aligned. The L293D motor driver uses these velocity values to control the left and right motors, adjusting the robot's movement accordingly.

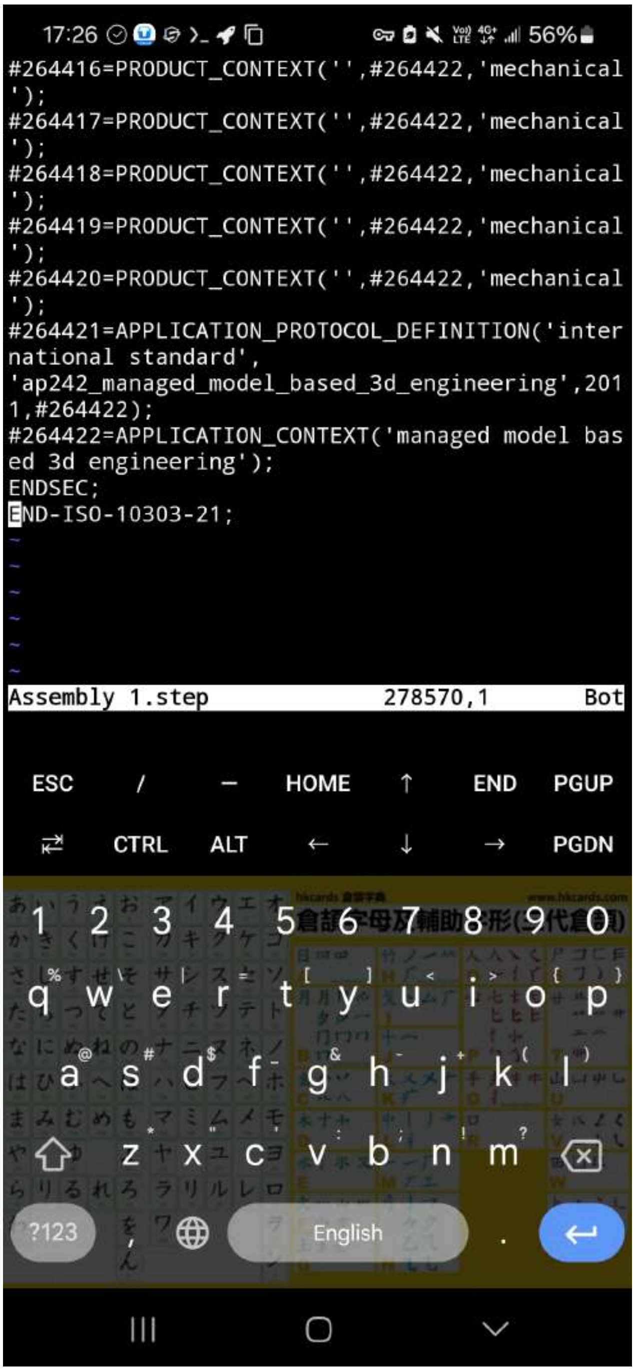
九、 Working Screenshots



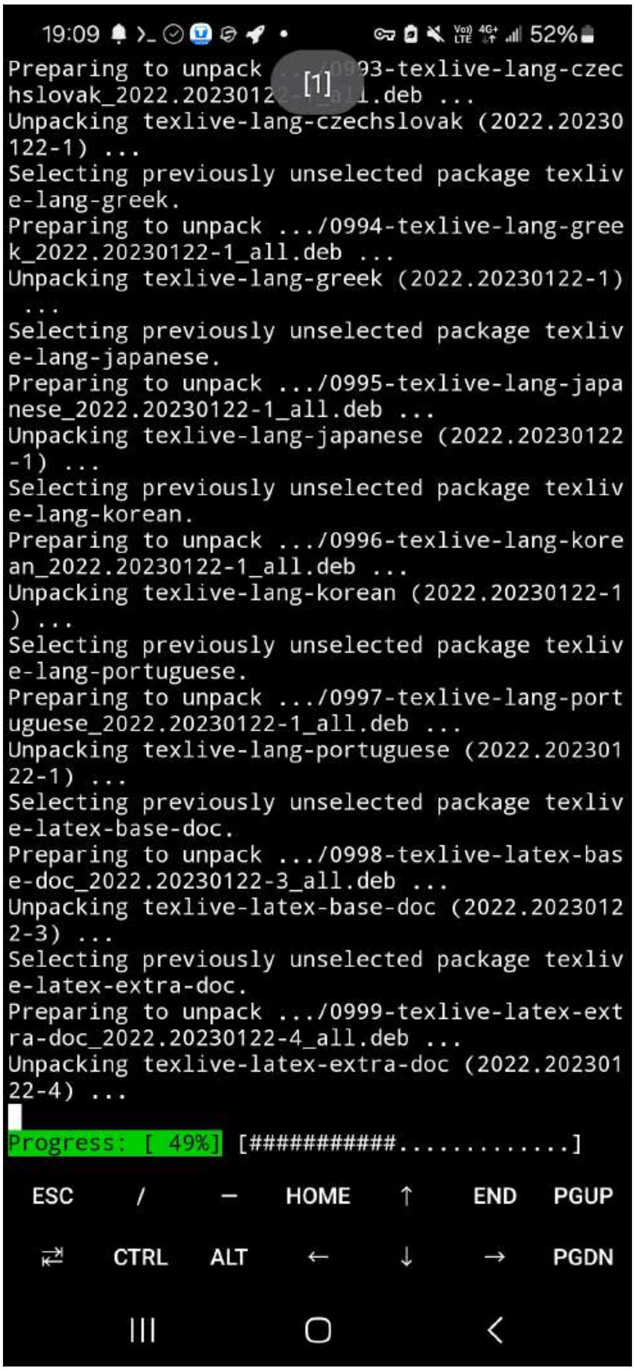
```
Writing objects:  92% (460/500), 2.99 MiB | 1.
Writing objects:  93% (465/500), 2.99 MiB | 1.
Writing objects:  94% (470/500), 2.99 MiB | 1.
Writing objects:  94% (471/500), 2.99 MiB | 1.
Writing objects:  94% (471/500), 3.82 MiB | 1.
Writing objects:  94% (472/500), 4.57 MiB | 1.
Writing objects:  94% (472/500), 5.03 MiB | 1.
Writing objects:  94% (473/500), 6.01 MiB | 88
Writing objects:  95% (475/500), 6.55 MiB | 76
Writing objects:  95% (475/500), 7.17 MiB | 81
Writing objects:  95% (476/500), 8.23 MiB | 95
Writing objects:  95% (477/500), 9.19 MiB | 98
Writing objects:  95% (478/500), 9.73 MiB | 97
Writing objects:  96% (480/500), 10.30 MiB | 1
Writing objects:  96% (481/500), 10.86 MiB | 9
Writing objects:  96% (482/500), 11.90 MiB | 9
Writing objects:  96% (484/500), 12.66 MiB | 9
Writing objects:  97% (485/500), 12.95 MiB | 8
Writing objects:  97% (486/500), 13.37 MiB | 8
Writing objects:  97% (487/500), 13.80 MiB | 8
Writing objects:  97% (487/500), 14.37 MiB | 7
Writing objects:  97% (487/500), 14.99 MiB | 6
Writing objects:  98% (490/500), 15.30 MiB | 5
Writing objects:  98% (491/500), 15.87 MiB | 5
Writing objects:  98% (492/500), 16.41 MiB | 5
Writing objects:  98% (492/500), 17.04 MiB | 5
Writing objects:  98% (492/500), 17.62 MiB | 5
Writing objects:  98% (493/500), 18.13 MiB | 4
Writing objects:  98% (494/500), 18.41 MiB | 5
Writing objects:  99% (495/500), 18.41 MiB | 5
Writing objects:  99% (496/500), 18.82 MiB | 5
Writing objects:  99% (498/500), 19.52 MiB | 5
Writing objects: 100% (500/500), 19.52 MiB | 5
Writing objects: 100% (500/500), 19.81 MiB | 7
70.00 KiB/s, done.
Total 500 (delta 282), reused 1 (delta 0), pac
k-reused 0 (from 0)
remote: Resolving deltas: 100% (282/282), comp
leted with 2 local objects.
To https://github.com/Willie169/PID.git
   691468c..c948790  main -> main
~/gh/PID $
```



```
 delete mode 100644 assets/Assembly 1/Assembly
 1.x_t
 delete mode 100755 assets/board.step
 create mode 100755 model_images/18650  batter
y.png
 create mode 100755 model_images/Assembly 1 (1
).png
 create mode 100755 model_images/Assembly 1 (2
).png
 create mode 100755 model_images/Assembly 1 (3
).png
 create mode 100755 model_images/Assembly 1 (4
).png
 create mode 100755 model_images/Assembly 1 (5
).png
 create mode 100755 model_images/Assembly 1 (6
).png
 create mode 100755 model_images/Assembly 1.pn
g
 create mode 100755 model_images/BATTERY HOLDE
R x2 18650 parts.png
 create mode 100755 model_images/BATTERY HOLDE
R x2 parts.png
 create mode 100755 model_images/HC-04HC-04 pa
rts.png
 create mode 100755 model_images/HC-04HC-04.pn
g
 create mode 100755 model_images/MiniBreadboar
d.png
 create mode 100755 model_images/One side TT M
otor v1.png
 create mode 100755 model_images/Part Studio 1
 (1).png
 create mode 100755 model_images/Part Studio 1
.png
 create mode 100755 model_images/Porta bateria
s 2x18650 (1).png
 create mode 100755 model_images/Porta bateria
s 2x18650.png
 create mode 100755 model_images/Screenshot_20
250101_235218_Chrome Beta.jpg
 create mode 100755 model_images/Screenshot_20
```

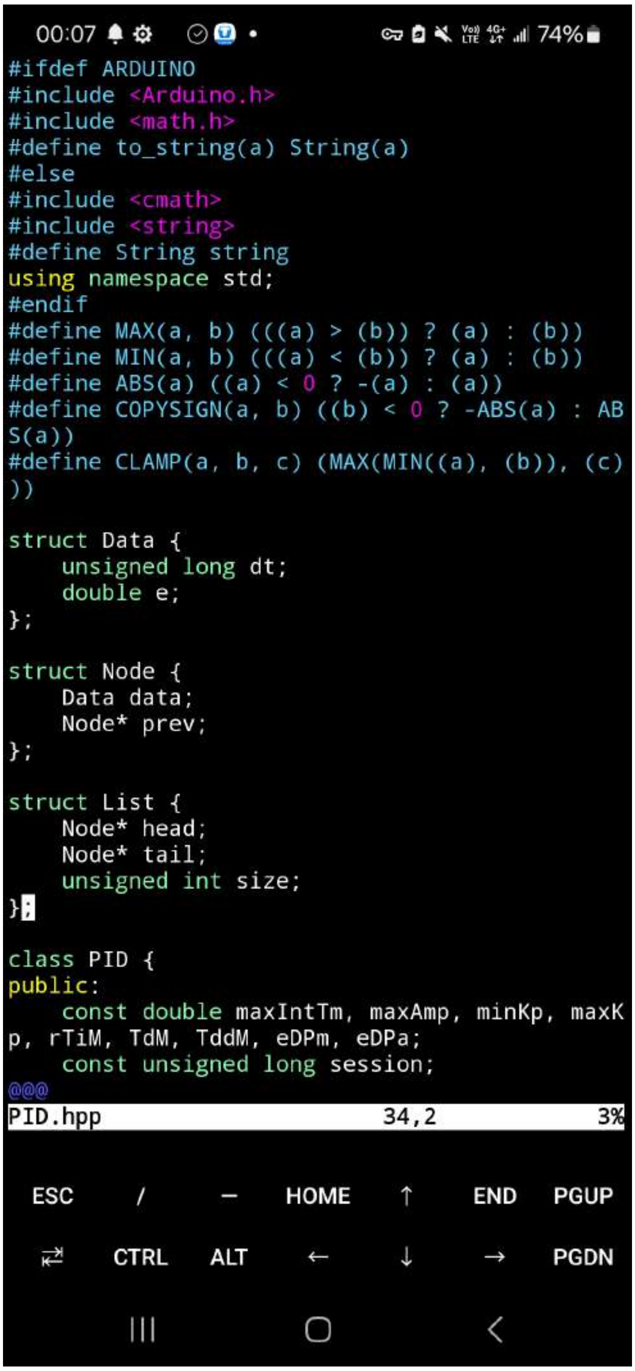


```
#264416=PRODUCT_CONTEXT('',#264422,'mechanical
');
#264417=PRODUCT_CONTEXT('',#264422,'mechanical
');
#264418=PRODUCT_CONTEXT('',#264422,'mechanical
');
#264419=PRODUCT_CONTEXT('',#264422,'mechanical
');
#264420=PRODUCT_CONTEXT('',#264422,'mechanical
');
#264421=APPLICATION_PROTOCOL_DEFINITION('inter
national standard',
'ap242_managed_model_based_3d_engineering',201
1,#264422);
#264422=APPLICATION_CONTEXT('managed model bas
ed 3d engineering');
ENDSEC;
END-ISO-10303-21;
~
~
~
~
~
~
Assembly 1.step              278570,1        Bot
```



```
Preparing to unpack .../0993-texlive-lang-czec
hslovak_2022.20230122-1_all.deb ...
Unpacking texlive-lang-czechslovak (2022.20230
122-1) ...
Selecting previously unselected package texliv
e-lang-greek.
Preparing to unpack .../0994-texlive-lang-gree
k_2022.20230122-1_all.deb ...
Unpacking texlive-lang-greek (2022.20230122-1)
 ...
Selecting previously unselected package texliv
e-lang-japanese.
Preparing to unpack .../0995-texlive-lang-japa
nese_2022.20230122-1_all.deb ...
Unpacking texlive-lang-japanese (2022.20230122
-1) ...
Selecting previously unselected package texliv
e-lang-korean.
Preparing to unpack .../0996-texlive-lang-kore
an_2022.20230122-1_all.deb ...
Unpacking texlive-lang-korean (2022.20230122-1
) ...
Selecting previously unselected package texliv
e-lang-portuguese.
Preparing to unpack .../0997-texlive-lang-port
uguese_2022.20230122-1_all.deb ...
Unpacking texlive-lang-portuguese (2022.202301
22-1) ...
Selecting previously unselected package texliv
e-latex-base-doc.
Preparing to unpack .../0998-texlive-latex-bas
e-doc_2022.20230122-3_all.deb ...
Unpacking texlive-latex-base-doc (2022.2023012
2-3) ...
Selecting previously unselected package texliv
e-latex-extra-doc.
Preparing to unpack .../0999-texlive-latex-ext
ra-doc_2022.20230122-4_all.deb ...
Unpacking texlive-latex-extra-doc (2022.202301
22-4) ...

Progress: [ 49%] [###########...........]
```



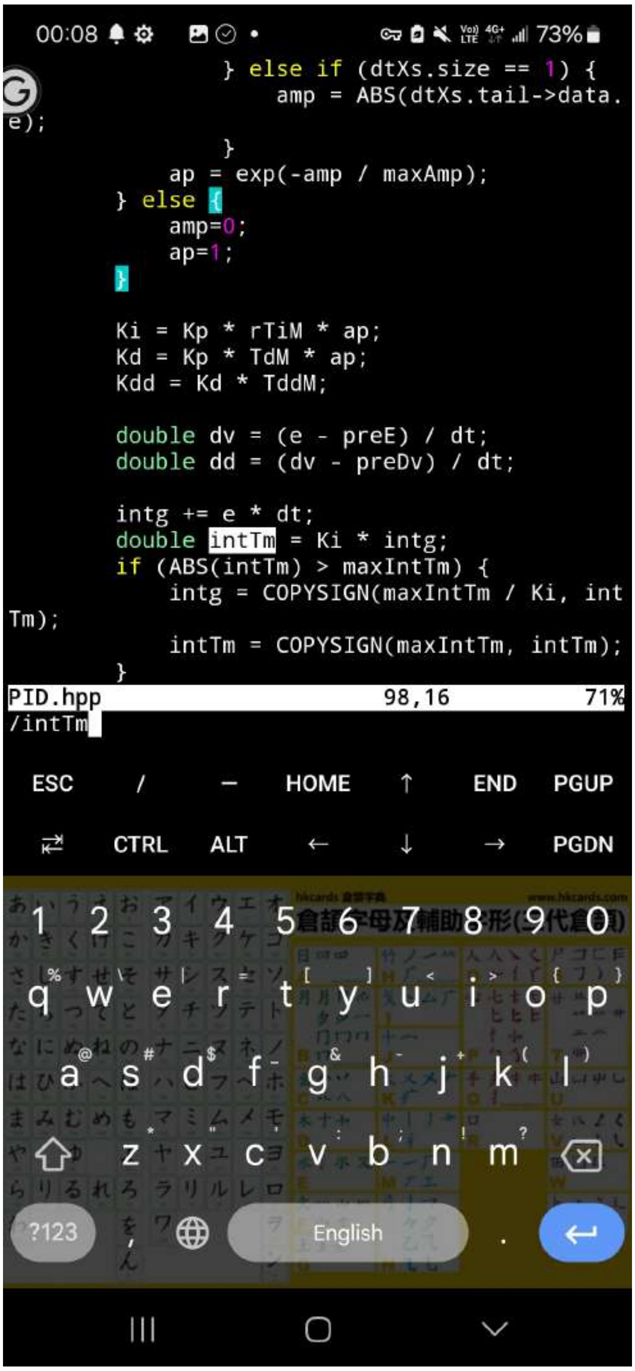
```
#ifdef ARDUINO
#include <Arduino.h>
#include <math.h>
#define to_string(a) String(a)
#else
#include <cmath>
#include <string>
#define String string
using namespace std;
#endif
#define MAX(a, b) (((a) > (b)) ? (a) : (b))
#define MIN(a, b) (((a) < (b)) ? (a) : (b))
#define ABS(a) ((a) < 0 ? -(a) : (a))
#define COPYSIGN(a, b) ((b) < 0 ? -ABS(a) : AB
S(a))
#define CLAMP(a, b, c) (MAX(MIN((a), (b)), (c)
))

struct Data {
    unsigned long dt;
    double e;
};

struct Node {
    Data data;
    Node* prev;
};

struct List {
    Node* head;
    Node* tail;
    unsigned int size;
};

class PID {
public:
    const double maxIntTm, maxAmp, minKp, maxK
p, rTiM, TdM, TddM, eDPm, eDPa;
    const unsigned long session;
@@@
PID.hpp                              34,2          3%
```



```
                } else if (dtXs.size == 1) {
                    amp = ABS(dtXs.tail->data.
e);
                }
            ap = exp(-amp / maxAmp);
        } else {
            amp=0;
            ap=1;
        }

        Ki = Kp * rTiM * ap;
        Kd = Kp * TdM * ap;
        Kdd = Kd * TddM;

        double dv = (e - preE) / dt;
        double dd = (dv - preDv) / dt;

        intg += e * dt;
        double intTm = Ki * intg;
        if (ABS(intTm) > maxIntTm) {
            intg = COPYSIGN(maxIntTm / Ki, int
Tm);
            intTm = COPYSIGN(maxIntTm, intTm);
        }
PID.hpp                          98,16          71%
/intTm
```

第六節　Report Writing

一、　My LaTeX Learning Journey

My journey with LaTeX began when I realized the limitations of traditional word processors for creating professional-looking documents, especially those involving mathematical equations and technical formatting. These features are critical for my studies and research in advanced mathematics and physics.

With prior experience in programming languages such as HTML, C++, and JavaScript, I quickly grasped the basic syntax of LaTeX. I created numerous LaTeX documents on math and science, including my **tw-gifted-k12-notes** (https://github.com/Willie169/tw-gifted-k12-notes) project and many entries in my Learning Portfolio.

I expanded my knowledge of LaTeX packages and commands by consulting resources such as **Overleaf** (https://www.overleaf.com), **TeX - LaTeX Stack Exchange** (https://tex.stackexchange.com), and package documentation from **CTAN - Comprehensive TEX Archive Network** (https://ctan.org).

As I became more proficient in LaTeX, I ventured into designing templates specifically for XeTeX, with a focus on enhancing usability for CJK users.

二、 Template Design

When designing a template, I carefully select packages, fonts, and define custom commands to ensure compatibility with diverse document types. Below are the key aspects of my template:

- **Document Aesthetics:** Packages like `nowidow`, `titlesec`, and `titling` enable fine control over spacing, section styles, and title layouts.
- **Mathematical and Scientific Typesetting:** For advanced notations and formulae, I utilize packages such as `amsmath`, `mathtools`, `nicematrix`, `physics`, and `mhchem`.
- **Graphics and Tables:** The `graphicx`, `tikz`, `subcaption`, and `longtable` packages allow the creation of professional-quality tables and illustrations.
- **Fonts and Localization:** I integrate multilingual support with `fontspec`, `xeCJK`, and `zhnumber`, using fonts like TeX Gyre, STIX 2 Math, and Noto CJK to seamlessly handle Chinese and other non-Latin characters.
- **Customization:** Using `etoolbox`, `xparse`, and `tcolorbox`, I create reusable components and custom behaviors, such as styled boxes and command shortcuts.

The culmination of my efforts is a template available on GitHub (https://github.com/Willie169/LaTeX-ToolKit), which I have also used for this report.

三、 LaTeX Template Code

```
% template.tex of https://github.com/Willie169/LaTeX-ToolKit, licensed under either GPL-3.0-or-later or CC BY-SA 4.0-or-later.
\usepackage[defaultlines=8]{nowidow}
\usepackage[utf8]{inputenc}
\usepackage[T1]{fontenc}
\usepackage{etoolbox}
\usepackage{caption,fontspec,titlesec,titling,setspace,needspace,titletoc}
\usepackage{amsthm,amsmath,amsfonts,amssymb,dsfont,stmaryrd,mathtools,mathrsfs,textcomp,esint,textgreek}
\usepackage{diagbox,cellspace,array,booktabs,enumitem,graphicx,subcaption,float,placeins}
\usepackage{tikz,xparse,physics,braket,nicematrix,longtable,hanging,chemfig}
\usepackage{url,hyperref,listings,csvsimple,pdfpages,metalogo}
\usepackage[version=4]{mhchem}
\usepackage{tcolorbox,xcolor,unicode-math}
\tcbuselibrary{listings,skins,breakable}
```

```
\makeatletter\tikzset{dot diameter/.store in=\dot@diameter,dot diameter=1pt,dot spacing/.store in=\dot@spacing,dot spacing=5.5pt,dots/.style={line width=\dot@diameter,line cap=round,dash pattern=on 0pt off \dot@spacing}}\makeatother
\ifnum\value{Fonts}=1
\setmainfont{TeX Gyre Heros}[Ligatures=TeX]
\setsansfont{TeX Gyre Termes}[Ligatures=TeX]
\setmonofont{Courier}[Ligatures=TeX]
\else\ifnum\value{Fonts}=2
\setmainfont{TeX Gyre Termes}[Ligatures=TeX]
\setsansfont{TeX Gyre Heros}[Ligatures=TeX]
\setmonofont{Courier}[Ligatures=TeX]
\else\ifnum\value{Fonts}=3
\setmainfont{TeX Gyre Heros}[Ligatures=TeX]
\setmonofont{Courier}[Ligatures=TeX]
\else\ifnum\value{Fonts}=4
\setmainfont{TeX Gyre Termes}[Ligatures=TeX]
\setmonofont{Courier}[Ligatures=TeX]
\else\ifnum\value{Fonts}=5
\setmainfont{TeX Gyre Heros}[Ligatures=TeX]
\setsansfont{TeX Gyre Termes}[Ligatures=TeX]
\else\ifnum\value{Fonts}=6
\setmainfont{TeX Gyre Termes}[Ligatures=TeX]
\setsansfont{TeX Gyre Heros}[Ligatures=TeX]
\else\ifnum\value{Fonts}=7
\setmainfont{TeX Gyre Heros}[Ligatures=TeX]
\else\ifnum\value{Fonts}=8
\setmainfont{TeX Gyre Termes}[Ligatures=TeX]
\fi\fi\fi\fi\fi\fi\fi\fi
\ifnum\value{STIXMath}=1\setmathfont{STIX Two Math}[Ligatures=TeX]\fi
\ifnum\value{xeCJK}=1
\usepackage[CJKspace]{xeCJK}
\usepackage{zhnumber}
\ifnum\value{ZhRenew}=1
\renewcommand{\contentsname}{\hfill\text{目錄}\hfill}
\else\ifnum\value{ZhRenew}=2
\renewcommand{\contentsname}{\hfill\text{目录}\hfill}
\fi\fi
\ifnum\value{CJKFonts}=0\else
\ifnum\value{CJKLanguage}=0
\ifnum\value{CJKFonts}=1
\setCJKmainfont{NotoSansTC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansTC-Regular.otf,ItalicFont=NotoSansTC-Medium.otf,BoldFont=NotoSansTC-Bold.otf,BoldItalicFont=NotoSansTC-Black.otf,SmallCapsFont=NotoSansTC-DemiLight.otf,Ligatures=TeX]\setCJKsansfont{NotoSerifTC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSerifTC-Regular.otf,ItalicFont=NotoSerifTC-Medium.otf,BoldFont=NotoSerifTC-Bold.otf,BoldItalicFont=NotoSerifTC-Black.otf,SmallCapsFont=NotoSerifTC-Light.otf,Ligatures=TeX]\setCJKmonofont{NotoSansMonoCJKtc}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansMonoCJKtc-Regular.otf,BoldFont=NotoSansMonoCJKtc-Bold.otf,Ligatures=TeX]
\else\ifnum\value{CJKFonts}=2
\setCJKmainfont{NotoSerifTC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSerifTC-Regular.otf,ItalicFont=NotoSerifTC-Medium.otf,BoldFont=NotoSerifTC-Bold.otf,BoldItalicFont=NotoSerifTC-Black.otf,SmallCapsFont=NotoSerifTC-Light.otf,Ligatures=TeX]\setCJKsansfont{NotoSansTC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansTC-Regular.otf,ItalicFont=NotoSansTC-Medium.otf,BoldFont=NotoSansTC-Bold.otf,BoldItalicFont=NotoSansTC-Black.otf,SmallCapsFont=NotoSansTC-DemiLight.otf,Ligatures=TeX]\setCJKmonofont{NotoSansMonoCJKtc}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansMonoCJKtc-Regular.otf,BoldFont=NotoSansMonoCJKtc-Bold.otf,Ligatures=TeX]
\else\ifnum\value{CJKFonts}=3
\setCJKmainfont{NotoSansTC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansTC-Regular.otf,ItalicFont=NotoSansTC-Medium.otf,BoldFont=NotoSansTC-Bold.otf,BoldItalicFont=NotoSansTC-Black.otf,SmallCapsFont=NotoSansTC-DemiLight.otf,Ligatures=TeX]\setCJKmonofont{NotoSansMonoCJKtc}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansMonoCJKtc-Regular.otf,BoldFont=NotoSansMonoCJKtc-Bold.otf,Ligatures=TeX]
\else\ifnum\value{CJKFonts}=4
\setCJKmainfont{NotoSerifTC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSerifTC-Regular.otf,ItalicFont=NotoSerifTC-Medium.otf,BoldFont=NotoSerifTC-Bold.otf,BoldItalicFont=NotoSerifTC-Black.otf,SmallCapsFont=NotoSerifTC-Light.otf,Ligatures=TeX]\setCJKmonofont{NotoSansMonoCJKtc}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansMonoCJKtc-Regular.otf,BoldFont=NotoSansMonoCJKtc-Bold.otf,Ligatures=TeX]
```

```
\else\ifnum\value{CJKFonts}=5
\setCJKmainfont{NotoSansTC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansTC-Regular.otf,ItalicFont=NotoSansTC-Medium.otf,BoldFont=NotoSansTC-Bold.otf,BoldItalicFont=NotoSansTC-Black.otf,SmallCapsFont=NotoSansTC-DemiLight.otf,Ligatures=TeX]\setCJKsansfont{NotoSerifTC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSerifTC-Regular.otf,ItalicFont=NotoSerifTC-Medium.otf,BoldFont=NotoSerifTC-Bold.otf,BoldItalicFont=NotoSerifTC-Black.otf,SmallCapsFont=NotoSerifTC-Light.otf,Ligatures=TeX]
\else\ifnum\value{CJKFonts}=6
\setCJKmainfont{NotoSerifTC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSerifTC-Regular.otf,ItalicFont=NotoSerifTC-Medium.otf,BoldFont=NotoSerifTC-Bold.otf,BoldItalicFont=NotoSerifTC-Black.otf,SmallCapsFont=NotoSerifTC-Light.otf,Ligatures=TeX]\setCJKsansfont{NotoSansTC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansTC-Regular.otf,ItalicFont=NotoSansTC-Medium.otf,BoldFont=NotoSansTC-Bold.otf,BoldItalicFont=NotoSansTC-Black.otf,SmallCapsFont=NotoSansTC-DemiLight.otf,Ligatures=TeX]
\else\ifnum\value{CJKFonts}=7
\setCJKmainfont{NotoSansTC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansTC-Regular.otf,ItalicFont=NotoSansTC-Medium.otf,BoldFont=NotoSansTC-Bold.otf,BoldItalicFont=NotoSansTC-Black.otf,SmallCapsFont=NotoSansTC-DemiLight.otf,Ligatures=TeX]
\else\ifnum\value{CJKFonts}=8
\setCJKmainfont{NotoSerifTC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSerifTC-Regular.otf,ItalicFont=NotoSerifTC-Medium.otf,BoldFont=NotoSerifTC-Bold.otf,BoldItalicFont=NotoSerifTC-Black.otf,SmallCapsFont=NotoSerifTC-Light.otf,Ligatures=TeX]
\fi\fi\fi\fi\fi\fi\fi\fi\else
\ifnum\value{CJKLanguage}=1
\ifnum\value{CJKFonts}=1
\setCJKmainfont{NotoSansSC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansSC-Regular.otf,ItalicFont=NotoSansSC-Medium.otf,BoldFont=NotoSansSC-Bold.otf,BoldItalicFont=NotoSansSC-Black.otf,SmallCapsFont=NotoSansSC-DemiLight.otf,Ligatures=TeX]\setCJKsansfont{NotoSerifSC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSerifSC-Regular.otf,ItalicFont=NotoSerifSC-Medium.otf,BoldFont=NotoSerifSC-Bold.otf,BoldItalicFont=NotoSerifSC-Black.otf,SmallCapsFont=NotoSerifSC-Light.otf,Ligatures=TeX]\setCJKmonofont{NotoSansMonoCJKsc}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansMonoCJKsc-Regular.otf,BoldFont=NotoSansMonoCJKsc-Bold.otf,Ligatures=TeX]
\else\ifnum\value{CJKFonts}=2
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\else\ifnum\value{CJKFonts}=3
\setCJKmainfont{NotoSansSC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansSC-Regular.otf,ItalicFont=NotoSansSC-Medium.otf,BoldFont=NotoSansSC-Bold.otf,BoldItalicFont=NotoSansSC-Black.otf,SmallCapsFont=NotoSansSC-DemiLight.otf,Ligatures=TeX]\setCJKmonofont{NotoSansMonoCJKsc}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansMonoCJKsc-Regular.otf,BoldFont=NotoSansMonoCJKsc-Bold.otf,Ligatures=TeX]
\else\ifnum\value{CJKFonts}=4
\setCJKmainfont{NotoSerifSC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSerifSC-Regular.otf,ItalicFont=NotoSerifSC-Medium.otf,BoldFont=NotoSerifSC-Bold.otf,BoldItalicFont=NotoSerifSC-Black.otf,SmallCapsFont=NotoSerifSC-Light.otf,Ligatures=TeX]\setCJKmonofont{NotoSansMonoCJKsc}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansMonoCJKsc-Regular.otf,BoldFont=NotoSansMonoCJKsc-Bold.otf,Ligatures=TeX]
\else\ifnum\value{CJKFonts}=5
\setCJKmainfont{NotoSansSC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansSC-Regular.otf,ItalicFont=NotoSansSC-Medium.otf,BoldFont=NotoSansSC-Bold.otf,BoldItalicFont=NotoSansSC-Black.otf,SmallCapsFont=NotoSansSC-DemiLight.otf,Ligatures=TeX]\setCJKsansfont{NotoSerifSC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSerifSC-Regular.otf,ItalicFont=NotoSerifSC-Medium.otf,BoldFont=NotoSerifSC-Bold.otf,BoldItalicFont=NotoSerifSC-Black.otf,SmallCapsFont=NotoSerifSC-Light.otf,Ligatures=TeX]
\else\ifnum\value{CJKFonts}=6
\setCJKmainfont{NotoSerifSC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSerifSC-Regular.otf,ItalicFont=NotoSerifSC-Medium.otf,BoldFont=NotoSerifSC-Bold.otf,BoldItalicFont=NotoSerifSC-Black.otf,SmallCapsFont=NotoSerifSC-Light.otf,Ligatures=TeX]\setCJKsansfont{NotoSansSC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansSC-Regular.otf,ItalicFont=NotoSansSC-Medium.otf,BoldFont=NotoSansSC-Bold.otf,BoldItalicFont=NotoSansSC-Black.otf,SmallCapsFont=NotoSansSC-DemiLight.otf,Ligatures=TeX]
\else\ifnum\value{CJKFonts}=7
\setCJKmainfont{NotoSansSC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSansSC-Regular.otf,ItalicFont=NotoSansSC-Medium.otf,BoldFont=NotoSansSC-Bold.otf,BoldItalicFont=NotoSansSC-Black.otf,SmallCapsFont=NotoSansSC-DemiLight.otf,Ligatures=TeX]
\else\ifnum\value{CJKFonts}=8
```

```
\setCJKmainfont{NotoSerifSC}[Path=/usr/share/fonts/noto-cjk/,UprightFont=NotoSerifSC-Regular.otf,ItalicFont=NotoSerifSC-Medium.otf,BoldFont=NotoSerifSC-Bold.otf,BoldItalicFont=NotoSerifSC-Black.otf,SmallCapsFont=NotoSerifSC-Light.otf,Ligatures=TeX]
\fi\fi\fi\fi\fi\fi\fi\fi\else
\ifnum\value{CJKLanguage}=2
\ifnum\value{CJKFonts}=1
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\captionsetup[subfigure]{labelformat=empty}
\renewcommand{\maketitle}{
\begin{titlepage}
\begin{center}
\vspace*{\fill}
{\huge \bfseries \thetitle\par}
\vskip 1.5em
{\Large \theauthor\par}
\vskip 1em
{\large \thedate\par}
\vspace*{\fill}
\end{center}
\end{titlepage}
}
\lstset{
basicstyle=\ttfamily\scriptsize,
keywordstyle=\color{blue},
stringstyle=\color{red},
commentstyle=\color{green!50!black},
numberstyle=\small\color{gray},
numbers=left,
stepnumber=1,
numbersep=5pt,
backgroundcolor=\color{white},
showspaces=false,
showstringspaces=false,
showtabs=false,
frame=single,
rulecolor=\color{black},
tabsize=4,
captionpos=b,
breaklines=true,
breakatwhitespace=false
```

```
}
\makeatletter\csvset{autotabularcenter/.style={file=#1,after head=\csv@pretable\begin{tabular}{|*{\csv@columncount}{c|}}\csv@tablehead,table head=\hline\csvlinetotablerow\\\hline,late after line=\\,lable foot=\\\hline,late after last line=\csv@tablefoot\end{tabular}\csv@posttable,command=\csvlinetotablerow},autobooktabularcenter/.style={file=#1,after head=\csv@pretable\begin{tabular}{*{\csv@columncount}{c}}\csv@tablehead,table head=\toprule\csvlinetotablerow\\\midrule,late after line=\\,table foot=\\\bottomrule,late after last line=\csv@tablefoot\end{tabular}\csv@posttable,command=\csvlinetotablerow}}\makeatother\newcommand{\csvautotabularcenter}[2][]{\csvloop{autotabularcenter={#2},#1}}\newcommand{\csvautobooktabularcenter}[2][]{\csvloop{autobooktabularcenter={#2},#1}}
\newtheorem{theorem}{Theorem}
\newtheorem{lemma}{Lemma}
\makeatletter
\newcommand{\overleftrightsmallarrow}{\mathpalette{\overarrowsmall@\leftrightarrowfill@}}
\newcommand{\overrightsmallarrow}{\mathpalette{\overarrowsmall@\rightarrowfill@}}
\newcommand{\overleftsmallarrow}{\mathpalette{\overarrowsmall@\leftarrowfill@}}
\newcommand{\overarrowsmall@}[3]{
\vbox{
\ialign{
##\crcr
#1{\smaller@style{#2}}\crcr
\noalign{\nointerlineskip}
$\m@th\hfil#2#3\hfil$\crcr
}
}
}
\def\smaller@style#1{
\ifx#1\displaystyle\scriptstyle\else
\ifx#1\textstyle\scriptstyle\else
\scriptscriptstyle
\fi
\fi
}
\makeatother
\ProvideDocumentCommand{\Arg}{}{\operatorname{Arg}}
\ProvideDocumentCommand{\Ns}{m}{\Needspace{#1}}
\ProvideDocumentCommand{\RNum}{m}{\uppercase\expandafter{\romannumeral #1\relax}}
\ProvideDocumentCommand{\acosh}{}{\operatorname{acosh}}
\ProvideDocumentCommand{\acos}{}{\operatorname{acos}}
\ProvideDocumentCommand{\acsch}{}{\operatorname{acsch}}
\ProvideDocumentCommand{\acsc}{}{\operatorname{acsc}}
\ProvideDocumentCommand{\and}{}{\&}
\ProvideDocumentCommand{\arccosh}{}{\operatorname{arccosh}}
\ProvideDocumentCommand{\arccsch}{}{\operatorname{arccsch}}
\ProvideDocumentCommand{\arccsc}{}{\operatorname{arccsc}}
\ProvideDocumentCommand{\arcsech}{}{\operatorname{arcsech}}
\ProvideDocumentCommand{\arcsec}{}{\operatorname{arcsec}}
\ProvideDocumentCommand{\arcsinh}{}{\operatorname{arcsinh}}
\ProvideDocumentCommand{\arctanh}{}{\operatorname{arctanh}}
\ProvideDocumentCommand{\asech}{}{\operatorname{asech}}
\ProvideDocumentCommand{\asec}{}{\operatorname{asec}}
\ProvideDocumentCommand{\asinh}{}{\operatorname{asinh}}
\ProvideDocumentCommand{\asin}{}{\operatorname{asin}}
\ProvideDocumentCommand{\atanh}{}{\operatorname{atanh}}
\ProvideDocumentCommand{\atantwo}{}{\operatorname{atan2}}
\ProvideDocumentCommand{\atan}{}{\operatorname{atan}}
\ProvideDocumentCommand{\bBNM}{}{\begin{BNiceMatrix}}
\ProvideDocumentCommand{\bBmt}{}{\begin{Bmatrix}}
\ProvideDocumentCommand{\bNM}{}{\begin{NiceMatrix}}
\ProvideDocumentCommand{\bsh}{}{\ifmmode\backslash\else\textbackslash\fi}
\ProvideDocumentCommand{\bVNM}{}{\begin{VNiceMatrix}}
\ProvideDocumentCommand{\bVmt}{}{\begin{Vmatrix}}
\ProvideDocumentCommand{\ba}{}{\begin{aligned}}
\ProvideDocumentCommand{\bbNM}{}{\begin{bNiceMatrix}}
\ProvideDocumentCommand{\bbmt}{}{\begin{bmatrix}}
\ProvideDocumentCommand{\bcs}{}{\begin{cases}}
```

```
\ProvideDocumentCommand{\bctf}{}{\begin{center}\centering\begin{figure}[H]}
\ProvideDocumentCommand{\bctt}{}{\begin{center}\centering\begin{table}[H]}
\ProvideDocumentCommand{\bct}{}{\begin{center}}
\ProvideDocumentCommand{\be}{}{\begin{equation}}
\ProvideDocumentCommand{\bfH}{}{\begin{figure}[H]}
\ProvideDocumentCommand{\bf}{}{\begin{figure}}
\ProvideDocumentCommand{\bg}{m}{\begin{#1}}
\ProvideDocumentCommand{\bmac}{}{\[\begin{aligned}\begin{cases}}
\ProvideDocumentCommand{\bma}{}{\[\begin{aligned}}
\ProvideDocumentCommand{\bmc}{}{\[\begin{cases}}
\ProvideDocumentCommand{\bmt}{}{\begin{matrix}}
\ProvideDocumentCommand{\bm}{}{\[}
\ProvideDocumentCommand{\bpNM}{}{\begin{pNiceMatrix}}
\ProvideDocumentCommand{\bpmt}{}{\begin{pmatrix}}
\ProvideDocumentCommand{\btH}{}{\begin{table}[H]}
\ProvideDocumentCommand{\btbr}{}{\begin{tabular}}
\ProvideDocumentCommand{\btk}{}{\begin{tikzpicture}}
\ProvideDocumentCommand{\bt}{}{\begin{table}}
\ProvideDocumentCommand{\bvNM}{}{\begin{vNiceMatrix}}
\ProvideDocumentCommand{\bvmt}{}{\begin{vmatrix}}
\ProvideDocumentCommand{\cds}{}{\cdots}
\ProvideDocumentCommand{\cd}{}{\cdot}
\ProvideDocumentCommand{\chf}{m}{\chemfig{#1}}
\ProvideDocumentCommand{\closure}{}{\operatorname{closure}}
\ProvideDocumentCommand{\col}{}{\operatorname{col}}
\ProvideDocumentCommand{\ctg}{O{} m o}{\begin{center}\begin{figure}[H]\centering\includegraphics[#1]{#2}\IfNoValueF{#3}{\caption{#3}}\end{figure}\FloatBarrier\end{center}}
\ProvideDocumentCommand{\ctr}{}{\centering}
\ProvideDocumentCommand{\dds}{}{\ddots}
\ProvideDocumentCommand{\df}{m m o}{\IfNoValueTF{#3}{\frac{\mathrm{d}#1}{\mathrm{d}#2}}{\frac{\mathrm{d}^{#1}#2}{\mathrm{d}#3^{#1}}}}
\ProvideDocumentCommand{\dpre}{m m o}{\IfNoValueTF{#3}{\frac{\mathrm{d}}{\mathrm{d}#2}\left(#1\right)}{\frac{\mathrm{d}^{#1}}{\mathrm{d}#3^{#1}}\left(#2\right)}}
\ProvideDocumentCommand{\eBNM}{}{\end{BNiceMatrix}}
\ProvideDocumentCommand{\eBmt}{}{\end{Bmatrix}}
\ProvideDocumentCommand{\eNM}{}{\end{NiceMatrix}}
\ProvideDocumentCommand{\eVNM}{}{\end{VNiceMatrix}}
\ProvideDocumentCommand{\eVmt}{}{\end{Vmatrix}}
\ProvideDocumentCommand{\eam}{}{\end{aligned}\]}
\ProvideDocumentCommand{\ea}{}{\end{aligned}}
\ProvideDocumentCommand{\ebNM}{}{\end{bNiceMatrix}}
\ProvideDocumentCommand{\ebmt}{}{\end{bmatrix}}
\ProvideDocumentCommand{\ecam}{}{\end{cases}\end{aligned}\]}
\ProvideDocumentCommand{\ecm}{}{\end{cases}\]}
\ProvideDocumentCommand{\ecs}{}{\end{cases}}
\ProvideDocumentCommand{\ect}{}{\end{center}}
\ProvideDocumentCommand{\ed}{m}{\end{#1}}
\ProvideDocumentCommand{\ee}{}{\end{equation}}
\ProvideDocumentCommand{\ef}{}{\end{figure}}
\ProvideDocumentCommand{\efB}{}{\end{figure}\FloatBarrier}
\ProvideDocumentCommand{\efct}{}{\end{figure}\FloatBarrier\end{center}}
\ProvideDocumentCommand{\emt}{}{\end{matirx}}
\ProvideDocumentCommand{\em}{}{\]}
\ProvideDocumentCommand{\epNM}{}{\end{pNiceMatrix}}
\ProvideDocumentCommand{\epmt}{}{\end{pmatrix}}
\ProvideDocumentCommand{\eq}{}{=}
\ProvideDocumentCommand{\etB}{}{\end{table}\FloatBarrier}
\ProvideDocumentCommand{\etbr}{}{\end{tabular}}
\ProvideDocumentCommand{\etct}{}{\end{table}\FloatBarrier\end{center}}
\ProvideDocumentCommand{\etk}{}{\end{tikzpicture}}
\ProvideDocumentCommand{\et}{}{\end{table}}
\ProvideDocumentCommand{\evNM}{}{\end{vNiceMatrix}}
\ProvideDocumentCommand{\evmt}{}{\end{vmatrix}}
\ProvideDocumentCommand{\f}{m m}{\frac{#1}{#2}}
\ProvideDocumentCommand{\fr}{m m}{\frac{#1}{#2}}
```

```latex
\ProvideDocumentCommand{\gt}{}{>}
\ProvideDocumentCommand{\hf}{}{\hfill}
\ProvideDocumentCommand{\hs}{m}{\hspace{#1}}
\ProvideDocumentCommand{\ht}{m}{\hat{#1}}
\ProvideDocumentCommand{\inft}{}{\infty}
\ProvideDocumentCommand{\ip}{m}{\input{#1}}
\ProvideDocumentCommand{\itg}{m m o o}{\IfNoValueTF{#4}{\IfNoValueTF{#3}{\int #1\,\mathrm{d}{#2}}{\int_0^{#1}#2\,\mathrm{d}{#3}}}{\int_{#1}^{#2} #3\,\mathrm{d}{#4}}}
\ProvideDocumentCommand{\lt}{}{<}
\ProvideDocumentCommand{\md}{O{}}{\[#1\]}
\ProvideDocumentCommand{\mi}{O{}}{\(#1\)}
\ProvideDocumentCommand{\mn}{}{-}
\ProvideDocumentCommand{\nth}{o}{\IfNoValueTF{#1}{\Needspace{1\textheight}}{\Needspace{#1\textheight}}}
\ProvideDocumentCommand{\nthm}{}{\Needspace{1\textheight-1em}}
\ProvideDocumentCommand{\null}{}{\operatorname{null}}
\ProvideDocumentCommand{\n}{}{\\}
\ProvideDocumentCommand{\ola}{m}{\overleftsmallarrow{#1}}
\ProvideDocumentCommand{\olra}{m}{\overleftrightsmallarrow{#1}}
\ProvideDocumentCommand{\ol}{m}{\overline{#1}}
\ProvideDocumentCommand{\opn}{m}{\operatorname{#1}}
\ProvideDocumentCommand{\ora}{m}{\overrightsmallarrow{#1}}
\ProvideDocumentCommand{\parallelsum}{}{\mathbin{\!/\mkern-5mu/\!}}
\ProvideDocumentCommand{\pc}{}{\%}
\ProvideDocumentCommand{\pf}{m m o}{\IfNoValueTF{#3}{\frac{\partial #1}{\partial #2}}{\frac{\partial^{#1} #2}{\partial #3^{#1}}}}
\ProvideDocumentCommand{\pht}{m}{\phantom{#1}}
\ProvideDocumentCommand{\pl}{}{+}
\ProvideDocumentCommand{\ppre}{m m o}{\IfNoValueTF{#3}{\partial #2 \left( #1 \right)}{\frac{\partial^{#1}}{\partial #3^{#1}} \left( #2 \right)}}
\ProvideDocumentCommand{\rank}{}{\operatorname{rank}}
\ProvideDocumentCommand{\rl}{}{\relax}
\ProvideDocumentCommand{\sh}{}{/}
\ProvideDocumentCommand{\tc}{m}{\text{\raisebox{.6pt}{\textcircled{\raisebox{-.9pt}{#1}}}}}
\ProvideDocumentCommand{\tf}{m}{\textsf{#1}}
\ProvideDocumentCommand{\th}{}{\textheight}
\ProvideDocumentCommand{\ti}{m}{\textit{#1}}
\ProvideDocumentCommand{\tm}{}{\times}
\ProvideDocumentCommand{\ts}{o}{\IfNoValueTF{#1}{\text{\protect\ }}{\text{\protect\foreach\i in{1,2,...,#1}{\protect\ }}}}
\ProvideDocumentCommand{\tt}{m}{\texttt{#1}}
\ProvideDocumentCommand{\tw}{m}{\textwidth{#1}}
\ProvideDocumentCommand{\tx}{m}{\text{#1}}
\ProvideDocumentCommand{\vc}{m}{\vec{#1}}
\ProvideDocumentCommand{\vds}{}{\vdots}
\ProvideDocumentCommand{\vf}{}{\vfill}
\ProvideDocumentCommand{\vsf}{}{\vspace*{\fill}}
\ProvideDocumentCommand{\vs}{m}{\vspace{#1}}
\let\clp\clearpage
\let\FB\FloatBarrier
\let\La\Leftarrow
\let\Lra\Leftrightarrow
\let\Ra\Rightarrow
\let\icg\includegraphics
\let\la\leftarrow
\let\lds\ldots
\let\lra\leftrightarrow
\let\mb\mathbf
\let\mbb\mathbb
\let\mbf\mathbf
\let\mcl\mathcal
\let\mds\mathds
\let\mi\mathit
\let\ms\mathscr
\let\npgb\nopagebreak
\let\pgb\pagebreak
```

```latex
\let\ra\rightarrow
\let\rlh\rightleftharpoon
\let\tb\textbf
\titleclass{\subsubparagraph}{straight}[\subparagraph]
\newcounter{subsubparagraph}[subparagraph]
\titlespacing*{\subsubparagraph}{\parindent}{3.25ex plus 1ex minus .2ex}{1em}
\titleformat{\section}[block]{\Large\bfseries}{\thesection}{1em}{}
\titleformat{\subsection}{\large\bfseries}{\thesubsection}{1em}{}
\titleformat{\subsubsection}{\normalsize\bfseries}{\thesubsubsection}{1em}{}
\titleformat{\paragraph}{\normalsize\bfseries}{\theparagraph}{1em}{}
\titleformat{\subparagraph}{\normalsize\bfseries}{\thesubparagraph}{1em}{}
\titleformat{\subsubparagraph}{\normalsize\bfseries}{\thesubsubparagraph}{1em}{}
\ProvideDocumentCommand{\sct}{s o}{\IfBooleanTF{#1}{\IfNoValueTF{#2}{\section*}{\section*{#2}}}{\IfNoValueTF{#2}{\section}{\section{#2}}}}
\ProvideDocumentCommand{\ssc}{s o}{\IfBooleanTF{#1}{\IfNoValueTF{#2}{\subsection*}{\subsection*{#2}}}{\IfNoValueTF{#2}{\subsection}{\subsection{#2}}}}
\ProvideDocumentCommand{\sssc}{s o}{\IfBooleanTF{#1}{\IfNoValueTF{#2}{\subsubsection*}{\subsubsection*{#2}}}{\IfNoValueTF{#2}{\subsubsection}{\subsubsection{#2}}}}
\ProvideDocumentCommand{\pr}{s o}{\IfBooleanTF{#1}{\IfNoValueTF{#2}{\paragraph*}{\paragraph*{#2}}}{\IfNoValueTF{#2}{\paragraph}{\paragraph{#2}}}}
\ProvideDocumentCommand{\spr}{s o}{\IfBooleanTF{#1}{\IfNoValueTF{#2}{\subparagraph*}{\subparagraph*{#2}}}{\IfNoValueTF{#2}{\subparagraph}{\subparagraph{#2}}}}
\ProvideDocumentCommand{\sspr}{s o}{\IfBooleanTF{#1}{\IfNoValueTF{#2}{\subsubparagraph*}{\subsubparagraph*{#2}}}{\IfNoValueTF{#2}{\subsubparagraph}{\subsubparagraph{#2}}}}
\renewcommand\theparagraph{\arabic{paragraph}.}
\renewcommand\thesubparagraph{(\arabic{subparagraph})}
\renewcommand\thesubsubparagraph{\boxed{\arabic{subsubparagraph}}}
\titlecontents{section}[2em]{\addvspace{1em}}{\thecontentslabel\quad}{}{\titlerule*[1pc]{.}\contentspage}
\titlecontents{subsection}[4em]{\addvspace{0.5em}}{\thecontentslabel\quad}{}{\titlerule*[1pc]{.}\contentspage}
\titlecontents{subsubsection}[6em]{\addvspace{0.5em}}{\thecontentslabel\ }{}{\titlerule*[1pc]{.}\contentspage}
\ifnum\value{xeCJK}=1
\ifnum\value{SectionLanguage}=1
\renewcommand\thesection{第\zhnumber[style={Traditional,Normal}]{\arabic{section}}節}
\renewcommand\thesubsection{\zhnumber[style={Traditional,Normal}]{\arabic{subsection}}、}
\renewcommand\thesubsubsection{(\zhnumber[style={Traditional,Normal}]{\arabic{subsubsection}})}
\else\ifnum\value{SectionLanguage}=2
\renewcommand\thesection{第\zhnumber[style={Simplified,Normal}]{\arabic{section}}节}
\renewcommand\thesubsection{\zhnumber[style={Simplified,Normal}]{\arabic{subsection}}、}
\renewcommand\thesubsubsection{(\zhnumber[style={Simplified,Normal}]{\arabic{subsubsection}})}
\else
\renewcommand\thesection{\arabic{section}}
\renewcommand\thesubsection{\Roman{subsection}}
\renewcommand\thesubsubsection{\roman{subsubsection}}
\fi\fi
\else
\renewcommand\thesection{\arabic{section}}
\renewcommand\thesubsection{\Roman{subsection}}
\renewcommand\thesubsubsection{\roman{subsubsection}}
\fi
\makeatletter
\@ifclassloaded{article}{}{
\titleformat{\chapter}[block]{\LARGE\bfseries}{\thechapter}{1em}{}
\ProvideDocumentCommand{\ch}{s o}{\IfBooleanTF{#1}{\IfNoValueTF{#2}{\chapter*}{\chapter*{#2}}}{\IfNoValueTF{#2}{\chapter}{\chapter{#2}}}}
\titlecontents{chapter}[0em]{\addvspace{1em}}{\thecontentslabel\quad}{}{\titlerule*[1pc]{.}\contentspage}
\ifnum\value{xeCJK}=1
\ifnum\value{SectionLanguage}=1
\renewcommand\thechapter{第\zhnumber[style={Traditional,Normal}]{\arabic{chapter}}章}
\else\ifnum\value{SectionLanguage}=2
\renewcommand\thechapter{第\zhnumber[style={Simplified,Normal}]{\arabic{chapter}}章}
\else
\renewcommand\thechapter{Chapter \arabic{chapter}}
\fi\fi
\else
\renewcommand\thechapter{Chapter \arabic{chapter}}
\fi
}
\makeatother
\ifnum\value{xeCJK}=1\ifnum\value{ZhRenew}=0
\newcommand{\temtoday}{\today}
\else
\newcommand{\temtoday}{\zhtoday}
\fi\else
\newcommand{\temtoday}{\today}
\fi
\newcommand{\temtitle}{\thispagestyle{empty}\nth\maketitle\setcounter{page}{1}}
\newcommand{\temtoc}{\nth\tableofcontents}
\newcommand{\temdoc}{\nthm\setcounter{page}{1}}
\newcommand{\titletocdoc}{\onehalfspacing\temtitle\temtoc\temdoc}
\newcommand{\titledoc}{\onehalfspacing\temtitle\temdoc}
\newcommand{\tocdoc}{\onehalfspacing\temtoc\temdoc}
```