To run the project three C++ files have been updated. The files are main.cpp, pid_controller.cpp and pid_controller.h

pid_controller.cpp
In this class four main functions have been developed. The first function was

```
void PID::Init(double Kpi, double Kii, double Kdi, double output_lim_maxi,
double output_lim_mini)
```

In this function, we define the main variables for PID controller which are proportional, integral and derivative initial gains along with the minimum and maximum values for control action.

```
  Kp = Kpi;
  Ki = Kii;
  Kd = Kdi;
  output_lim_max = output_lim_maxi;
  output_lim_min = output_lim_mini;
  cte_last = 0;
  double integral_part = 0;
```

The next function is:

```
void PID::UpdateError(double cte)
```

In this function, we define the control actions calculated by proportional, integral and derivative components and add them together. The input to the function is error.

```
if (abs(time_step)<0.00001) return;
  double proportional_part = Kp * cte;
  integral_part += Ki * time_step * cte;
  double differential_part = Kd * (cte-cte_last)/time_step;
  double control_action = proportional_part + integral_part +
differential_part;
  cte_last = cte;
```

The third function is:

```
double PID::TotalError()
```

In this function, we check if the control action is within the minimum and maximum values. If not, either minimum or maximum value will be assigned to the control action.

The last function is

```
double PID::UpdateDeltaTime(double new_delta_time) {
   /**
   * TODO: Update the delta time with new value
   */
     time_step = new_delta_time;

      return time_step;
```

In this function, we update the time step at each iteration.

Pid_controller.h

In this file we define the PID class and its constructors:

```
class PID {
public:

     double cte_last;

     double Kp;
     double Ki;
     double Kd;

    double control_action;
     double output_lim_min;
     double output_lim_max;

     double time_step;
     double integral_part;


    /*
    * Constructor
    */
    PID();

    /*
    * Destructor.
    */
    virtual ~PID();

    /*
    * Initialize PID.
    */
    void Init(double Kp, double Ki, double Kd, double output_lim_max,
double output_lim_min);

    /*
    * Update the PID error variables given cross track error.
    */
    void UpdateError(double cte);

    /*
    * Calculate the total PID error.
    */
    double TotalError();

    /*
    * Update the delta time.
    */
    double UpdateDeltaTime(double new_delta_time);
};

#endif //PID_CONTROLLER_H
```

Main.cpp:

The first modification in this file was initialisation of PID controller for steering and throttle commands. To initialise the PID controllers, the initial values for Kp, Ki and Kd as well as the maximum and minimum of control actions were given as the input of the functions.

```
// initialize pid steer
  /**
  * TODO (Step 1): create pid (pid_steer) for steer command and initialize values
  **/
  PID pid_steer = PID();
  pid_steer.Init(0.5, 0.005, 0.5, 1.2, -1.2);


  // initialize pid throttle
  /**
  * TODO (Step 1): create pid (pid_throttle) for throttle command and initialize values
  **/
  PID pid_throttle = PID();
  pid_throttle.Init(0.5, 0.005, 0.5, 1.0, -1.0);
```

```
The next modification was the implementation of PID controller to adjust
steering command. Here, first we update the change in time step and then
calculate the steering error. Here, I have used the error in heading angle
instead of steering angle as both heading angle and steering angle are
indirectly related. Then, I used pid_steer.UpdateError function to
calculate the control action. Using pid_steer.TotalError when saturate
control actions between the minimum and maximum values of action for
safety reasons.
```

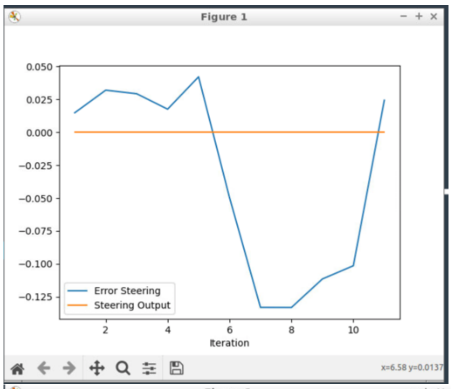
```
  ////////////////////////////////////////
          // Steering control
          ////////////////////////////////////////
          pid_steer.UpdateDeltaTime(new_delta_time);


          double error_steer;

          double steer_output;

          double yaw_new = angle_between_points(x_points[x_points.size()-
2], y_points[y_points.size()-2], x_points[x_points.size()-1],
y_points[y_points.size()-1]);
          error_steer = yaw_new - yaw;


          pid_steer.UpdateError(error_steer);
          steer_output = pid_steer.TotalError();
```

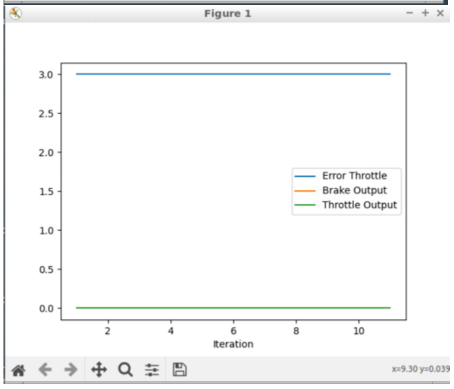
I followed the same thermology to calculate control action to control the throttle.

```
// Throttle control
          ////////////////////////////////////////

          /**
          * TODO (step 2): uncomment these lines
          **/
          // Update the delta time with the previous command
          pid_throttle.UpdateDeltaTime(new_delta_time);

          // Compute error of speed
          double error_throttle;
          /**
          * TODO (step 2): compute the throttle error (error_throttle) from the position and the
desired speed
          **/
          // modify the following line for step 2
          error_throttle = v_points.back() - velocity;


          double throttle_output;
          double brake_output;

          /**
          * TODO (step 2): uncomment these lines
          **/
          // Compute control to apply
          pid_throttle.UpdateError(error_throttle);
          double throttle = pid_throttle.TotalError();
```

Results:

The figure belows show the results. Unfortunately, the results are not correct. As the figures show, the steering controller is not able to direct error to zero and throttle control does no action.





Answer the following questions:

1- Add the plots to your report and explain them (describe what you see)

The file just plots the steering output. For some reasons the reference trajectory is zero and the error is high. I tried to find the source of the problem but I couldn't find it. I don't know why the file does not plot the other errors.

2- What is the effect of the PID according to the plots, how each part of the PID affects the control command?

Proportional controller directs the error towards zero but the large values may unstablise the system. Differential controller improve the stability of the system and integral controller helps to remove the steady state error as explained in the lecture video.

3- How would you design a way to automatically tune the PID parameters?

The most interesting approach is to use reinforcement learning technique to update automatically the gains of PID controllers real-time according to driving conditions. Also, it is possible to use classical control techniques such as adaptive controllers to automatically tune the PID gains.

4- PID controller is a model free controller, i.e. it does not use a model of the car. Could you explain the pros and cons of this type of controller?

The model free control systems such as PID controller make the controller robust against model uncertainties and parameter variations but tunning the gains is a challenge. Another example of model free controllers is reinforcement learning controllers such as value-based techniques and actor-critic techniques.

5- (Optional) What would you do to improve the PID controller?

Certainly, automatic real-time tuning of PID gains is a great improvements. But other techniques such is integral wind-up can be used to improve the error accumulation due to the integral part of PID controller.