INTELLIGENT ROBOTICS, PORTLAND STATE UNIVERSITY

Winter Report

Quaternion Attitude Control of a Simulated Airplane

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1. CHANGES TO LAST TERM'S CODE

I made the fuzzy-altitude controller from last term into a ROS service server. This is to control the attitude setpoint and enable/disable the controller from a separate ROS node. My plan is to have the altitude and attitude controller nodes given commands by a master "State Machine" node.

2. QUATERNION CONTROL

I. Why quaternion?

Traditional attitude controllers for aircraft use Euler angles to determine orientation. Euler angles are great because they are intuitive to conceptualize and implement, but they have a major drawback. When an aircraft pitches up 90 degrees; yaw changes can no longer be tracked. Effectively losing a degree of freedom. Quaternions do not have this issue. But unlike Euler angles they are (in my experience) near impossible to visualize and conceptualize. Though surprisingly easy to implement as a controller.

II. controller layout

The quaternion attitude controller was modeled after the one described in Quaternion Attitude Control System of Highly Maneuverable Aircraft [1]. It is a cascading controller that takes a quaternion setpoint (q_{sp}) and quaternion measured (q_{meas}) as the initial inputs to a proportional controller. The outputs of the proportional controller are angular velocity setpoints for their respective x, y, and z access PID controllers. The secondary inputs to these PIDs are the current measured angular velocities. The final outputs are the positions of the airplane control surfaces (rudder, aileron, and elevator).

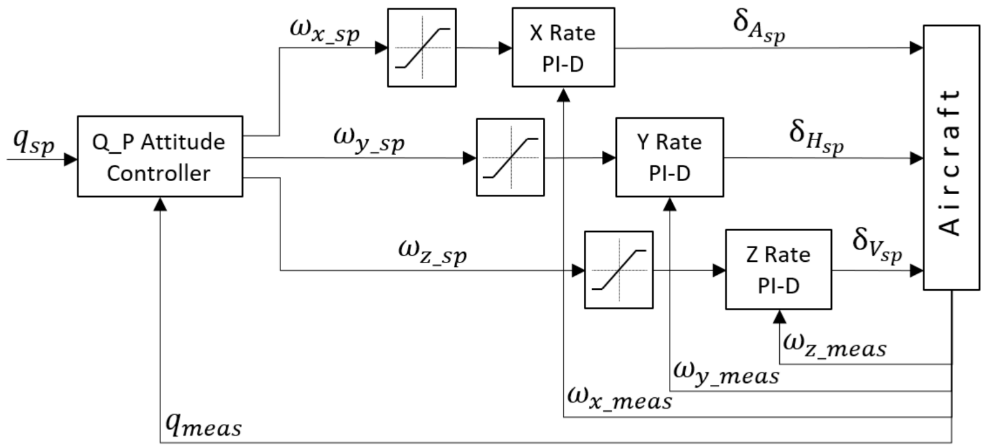


Figure 2.1: Quaternion-Based controller schematic from [1]

III. step by step

For the mathematical notation and in depth look for each step, please check pages 4-6 of Quaternion Attitude Control System of Highly Maneuverable Aircraft [1].
Here is my simplified step by step process:

1. Determine an orientation setpoint.
2. Find the orientation error by taking the Hamilton product between the conjugate of the measured orientation and the orientation setpoint.
   2.1. The measured orientation will be received from the onboard IMU.
3. If the scaler term of the orientation error quaternion is negative then set the orientation error quaternion equal to the negation of itself (not the complex conjugate!).
   3.1. This step is necissary because every quaternion orientation can be described by two separate rotations. This makes sure the shortest of the two rotations will be used.
4. Find the setpoint derivative by taking the proportional gain and multiplying it with the orientation error.
   4.1. The proportional gain is arbitrary. I have set it to 1.
   4.2. Since the derivative of direction is velocity, this derivative will result in angular velocity rates for each axis.
5. Find the angular velocity setpoints for their respective axis by taking the Hamilton product of 2 multiplied by the unit quaternion conjugate and the setpoint derivative.
   5.1. The unit quaternion formed when w=1, i=0, j=0, and k=0.
   5.2. Since the unit quaternion conjugate is equal to itself, just use the unit quaternion.
6. Use the resulting rate setpoints as the setpoints to their respective axis PID controller.
   6.1. Use the current angular velocity readings from the IMU for the measured values.
7. Send the outputs of each PID controller to their respective control surface. X to aileron, Y to Elevator, and Z to Rudder.

IV. Translating to python

To perform quaternion math I installed the numpy-quaternion version 2020.11.2.17.0.49 since that was the last version to support python 2.7. A dependency of numpy-quaternion is numba, which also must be explicitly installed to version 0.34.0. This quaternion library simplifies the process of performing quaternion math. It adds quaternions as a datatype to numpy. Hamilton products and quaternion conjugations become single function calls. Below is a snippet of code from the file attitude_control_gazebo.py that shows my implementation of the previous section's steps.

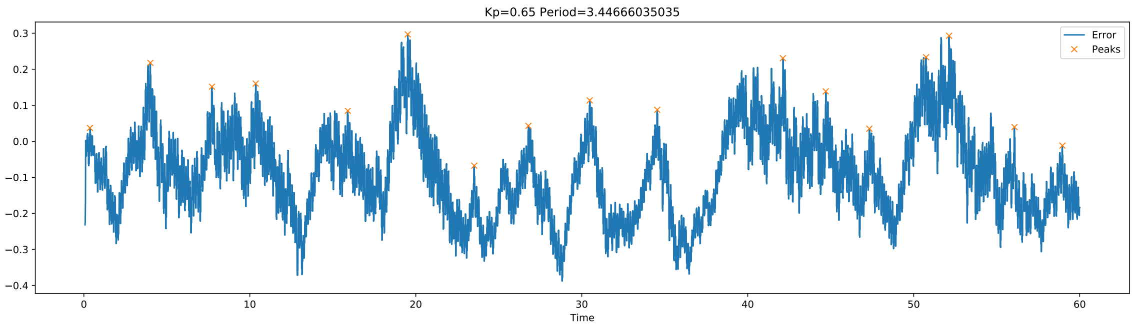
```python
import numpy as np
import quaternion

# Get measured attitude as quaternion
attitudeMeasured = np.quaternion(attitudeData.w,
                                 attitudeData.x,
                                 attitudeData.y,
                                 attitudeData.z
                                 )

# Get the attitude error
attitudeError =  np.multiply(np.conjugate(attitudeMeasured), attitudeSetpoint)

# Since 2 rotations can describe every attitude,
# find the shorter of both rotations
if attitudeError.w < 0:
    np.negative(attitudeError)

# Assume derivative of attitude setpoint is proportional to the attitude error
attitudeSetpointDerivative = Kp * attitudeError

# Declare unrotated unit quaternion
qU = np.quaternion(1,0,0,0)

# Get angular rate setpoints
rateSetpoints = np.multiply( (2 * qU) , attitudeSetpointDerivative)

# Give each PID controller the new setpoints
aeleronPID.setpoint   = rateSetpoints.x
elevatorPID.setpoint = rateSetpoints.y
rudderPID.setpoint    = rateSetpoints.z

# Get the positions for each control surface
msg.header.stamp = rospy.Time.now()
msg.x = aeleronPID(measuredangVelocity.x)
msg.y = elevatorPID(measuredangVelocity.y)
msg.z = rudderPID(measuredangVelocity.z)

# Publish the ROS commands
publisher.publish(msg)
```

I've set the gain Kp for the first Proportion controller to be a static 1 for now. I'm thinking to adjust this gain depending on the airspeed of the plane. The control surfaces have more influence over the aircraft at higher airspeeds, so I think making this gain inversely proportional to airspeed will allow for better control.

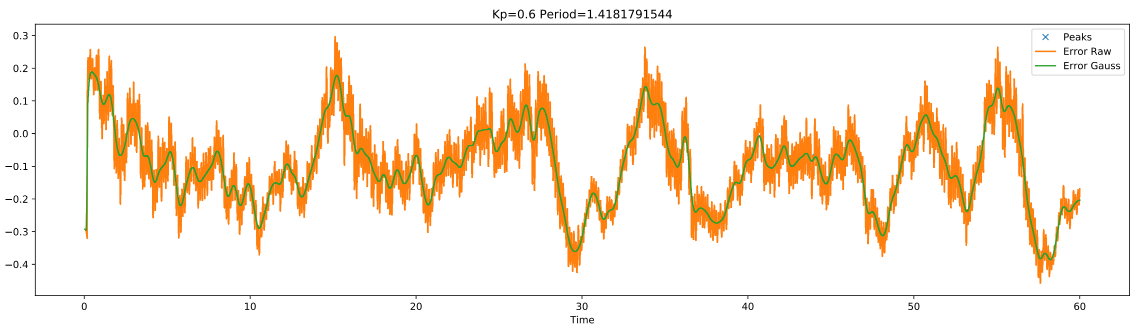
V. Controller Tuning

I am attempting to tune each PID controller separately. My plan was to find the "ultimate gain" as described by the Ziegler-Nicholas method. In which the Integral and Derivative Gains are set to 0, and the Proportional gain is adjusted until the system reaches a steady oscillation. The fist PID I tuned was for the elevator. I attempted to create a system to automatically find the ultimate gain. It works by recording the attitude error over time and determining when the error peaks appear. The more equidistant the peaks are then the more stable the oscillation. The peaks were found with the scipy.signal.find_peaks() function from the SciPy python library.

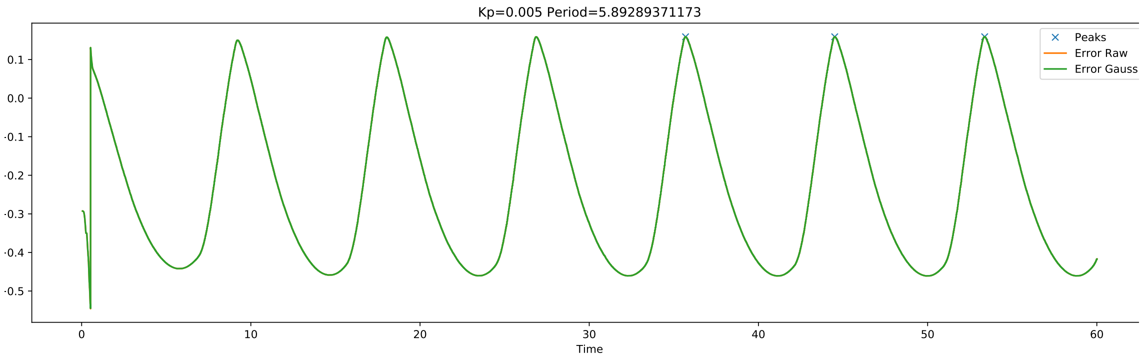
It is a deterministic system where the airplane was given an initial orientation of 8 degrees pitched up, a setpoint of level pitch, and 8m/s of initial velocity. The system would alter the gain value between 60 second trials to try to find the most stable oscillation. If the airplane lands on the ground then that trial has failed. There was a Lot of troubleshooting during this process. For Example:



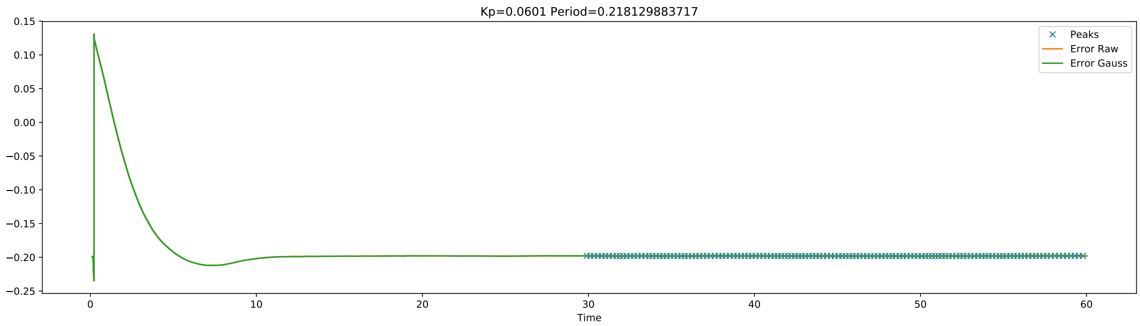
I thought the above graph showed a lot of noise so I added a 1-Dimensional Gaussian filter to help estimate actual error peaks. The filter is also a function of the SciPy library.



But it turns out it wasn't noise, but a consequence of using gain values far too high.

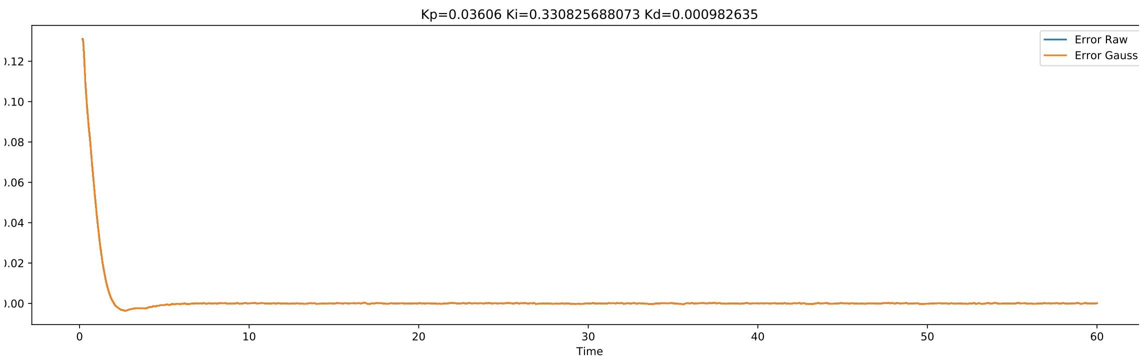


The graph above shows a gain with a steady oscillation, but it is involves the airplane repeatedly stalling.



I added a criteria to be minimizing the average distance between the error peaks and troughs and this is the Ultimate gain my final system came up with. The peaks only show on the graph half way through the trial because I set it to analyse after 30 seconds into the trials, allowing it to stabilize before calculating any period.

Plugging the ultimate gain into the Ziegler-Nichols formula:
$K_p = 0.7K_u$
$K_i = 1.2K_u/T_u$
$K_d = 0.075K_uT_u$



The controller gives minimal overshoot and stabilizes with minimal steady state error. I am very satisfied with this result.

3. THINGS TO DO

When trying to tune the system I was initially using the rosflight simulated IMU. It has a built in Kalman filter. The filter should get rid of any extraneous errors from the accelerometer and gyroscopic sensors, but even so the attitude would drift about 1 degree every 3 minutes. For a band-aid fix I changed from using the IMU to getting the exact attitude and velocity information from the Gazebo simulation's model. The IMU method will work but I will need to supplement the IMU data with a separate truth reference. I'll try using the simulated magnetometer sensor.

After tuning the aileron and rudder PIDs, next term will be focused on integrating the altitude and attitude controllers with the eyebrow detection convolution network. My current plan is to use a quaternion rotation $p' = qpq^{-1}$ to control pitch up/down and bank left/right. I will have the altitude controller do the "neutral" state.

I mostly work with embedded C. Therefore I'm still learning a lot about python. Something irritating I've found is that python has no static variables. I got around that by making too many variables global. In the future I will make functions that requires a static variable to be part of a class instead.

I. code

All files related to this project can be found at:
`https://github.com/Trenton-Ruf/Intelligent_Robotics`

Listing 1: attitude_control_gazebo.py

```
#!/usr/bin/env python

import rospy
from rosflight_msgs.msg import Command, Attitude
from nav_msgs.msg import Odometry
from simple_pid import PID
import numpy as np
import math
import quaternion # using version 2020.11.2.17.0.49
                  #numba dependency installed with "sudo apt install python-numba"
from scipy.signal import find_peaks
from scipy.ndimage.filters import gaussian_filter1d
import rospkg
from gazebo_msgs.msg import ModelState
from gazebo_msgs.srv import SetModelState
from gazebo_msgs.srv import GetModelState

from rosflight_control.srv import controller_set
import time
import matplotlib.pyplot as plt

attitude        = None
aeleronRate     = None
elevatorRate    = None
rudderRate      = None

enable = True;
# Initial setpoint value
attitudeSetpoint = np.quaternion(1,0,0,0)
#attitudeSetpoint = np.quaternion(0.991,0,0.131,0) # 15 degrees pitch up
#attitudeSetpoint = np.quaternion(0.998,0,0.07,0) # 8 degrees pitch up
```

```python

# unrotated unit quaternion
qU = np.quaternion(1,0,0,0)

# Atitude Proportional Controller Gain
Kp = 1

# create PID controllers
#elevatorPID = PID(0.055,0,0, setpoint=0)
elevatorPID = PID(0.01,0,0, setpoint=0) # getting integral

#aeleronPID = PID(0.1,0,0, setpoint=0)
#rudderPID = PID(0.1,0,0, setpoint=0)

aeleronPID = PID(0,0,0, setpoint=0)
rudderPID = PID(0,0,0, setpoint=0)

elevatorPID.output_limits = (-1,1) # Maximum elevator Deflections
aeleronPID.output_limits = (-1,1) # Maximum aeleron Deflections
rudderPID.output_limits  = (-1,1) # Maximum rudder Deflections

# Create Message Structure
msg = Command()

# msg.ignore = Command.IGNORE_X | Command.IGNORE_Z | Command.IGNORE_F
#msg.ignore = Command.IGNORE_F # Only ignore throttle at first
msg.F = 0.7 # Just for testing
msg.mode = Command.MODE_PASS_THROUGH

# Create publisher
publisher = rospy.Publisher("/fixedwing/command",Command, queue_size=1)

startTime = time.time()

def getFixedwingHeight():
    rospy.wait_for_service('/gazebo/get_model_state')
    try:
        get_state = rospy.ServiceProxy('/gazebo/get_model_state',GetModelState)
        resp = get_state('fixedwing',"")
        height = float(resp.pose.position.z)
        rospy.loginfo("fixedwing height: "+str(height))
        return height

    except rospy.ServiceExeption, e:
        print("Service call failed: %s" % e)



def resetState():
    state_msg = ModelState()
    state_msg.model_name = 'fixedwing'
    state_msg.pose.position.x = 0
    state_msg.pose.position.y = 0
    state_msg.pose.position.z = 20
    state_msg.pose.orientation.x = 0
    state_msg.pose.orientation.y = 0.131
    state_msg.pose.orientation.z = 0
    state_msg.pose.orientation.w = 0.991

    state_msg.twist.linear.x = 8

    rospy.wait_for_service('/gazebo/set_model_state')
```

```

    rospy.loginfo("Resetting State")

    try:
        set_state = rospy.ServiceProxy('/gazebo/set_model_state',SetModelState)
        resp = set_state(state_msg)
    except rospy.ServiceExeption, e:
        print("Service call failed: %s" % e)


def plotPID(x,y,gain):
    plt.rcParams["figure.figsize"] = (20,5)
    title = 'Kp='+str(gain)
    y_gauss = gaussian_filter1d(y, sigma=2)
    #peaks, properties = find_peaks(y_gauss,width=100,prominence=0.2)
    peaks, properties = find_peaks(y_gauss)
    if len(peaks) != 2:
        peak_timestamps= [x[i] for i in peaks if i > 30000]
        if len(peak_timestamps) != 0:
            peak_values = [y_gauss[i] for i in peaks if i > 30000]
            plt.plot(peak_timestamps, peak_values, 'x',label="Peaks")
            avg_period = (peak_timestamps[-1] - peak_timestamps[0]) / len(peak_timestamps)
            title += (' Period='+str(avg_period))
            rospy.loginfo("Plot Peaks: "+str(peaks))

    plt.plot(x,y, label = "Error Raw")
    plt.plot(x,y_gauss, label = "Error Gauss")
    plt.title(title)
    plt.xlabel('Time')
    plt.legend()
    #plt.savefig(str(gain)+'_PID.pdf')
    plt.show()
    plt.clf()


def findPeriodDeviation(_x,_y):
    deviation = -1
    y_gauss = gaussian_filter1d(_y, sigma=2)
    #peaks, properties = find_peaks(y_gauss,width=100,prominence=0.22)
    peaks, properties = find_peaks(y_gauss)
    rospy.loginfo("Peak indicies: "+str(peaks))
    if len(peaks) > 2:
        peak_timestamps = [_x[i] for i in peaks if i > 30000]
        if len(peak_timestamps) < 10:
            return deviation
        avg_period = (peak_timestamps[-1] - peak_timestamps[0]) / (len(peak_timestamps) -1 )

        #peak_debug = [_y[i] for i in peaks]
        #rospy.loginfo("Peak error: "+str(peak_debug))

        deviation = 0
        for index,timestamp in enumerate(peak_timestamps[:-1]):
            period = peak_timestamps[index+1] - timestamp
            deviation += abs(avg_period - period)
        deviation/len(peak_timestamps[:-1])
    return deviation

def findHeightDeviation(_x,_y):
    deviation = -1
    y_gauss = gaussian_filter1d(_y, sigma=2)
```

```python
    #peaks, properties = find_peaks(y_gauss, width=100,prominence=0.22)
    peaks, properties = find_peaks(y_gauss)
    troughs, properties = find_peaks(-y_gauss)
    #rospy.loginfo("Peak indicies: "+str(peaks))
    if len(peaks) > 2:
        peak_heights = [_y[i] for i in peaks if i > 30000]
        trough_depths = [_y[i] for i in troughs if i > 30000]
        if len(peak_heights) < 10:
            return deviation
        avg_height = sum(peak_heights) / len(peak_heights)
        avg_depth = sum(trough_depths) / len(trough_depths)
        deviation=0
        for index,height in enumerate(peak_heights):
            deviation += abs(avg_height - height)
        for index,depth in enumerate(trough_depths):
            deviation += abs(avg_depth - depth)
        return deviation * 100 * (avg_height - avg_depth)
    return deviation



ult_x = []
ult_y = []
y=[]
x=[]
best_gain = -1
old_best_gain = -1
inc_gain = 0.01
curr_gain = 0.01
target_gain = 0.1
precision = 5 # decimal points of precision
precision_count = 3
trial_duration = 60
def findUltimateGain(pid, error):
    global best_gain
    global inc_gain
    global curr_gain
    global target_gain
    global old_best_gain
    global startTime
    global ult_x
    global ult_y
    global precision_count

    # Only log the error and the time until trial finished
    elapsed_time = time.time() - startTime
    x.append(elapsed_time)
    y.append(error)
    if elapsed_time > trial_duration:
        plotPID(x,y,curr_gain) # Debug only
        startTime = time.time()
        rospy.loginfo("curr_gain: "+str(curr_gain))
        rospy.loginfo("best_gain: "+str(best_gain))
        rospy.loginfo("target_gain: "+str(target_gain))
        rospy.loginfo("inc_gain: "+str(inc_gain))
    else:
        return 0


    # Test curr against best
    deviation = findPeriodDeviation(x,y)
    deviation += findHeightDeviation(x,y)
```

```
    rospy.loginfo("deviation: "+str(deviation))
    if deviation >=0 and getFixedwingHeight() > 3:
        ult_deviation = findPeriodDeviation(ult_x,ult_y)
        ult_deviation += findHeightDeviation(ult_x,ult_y)
        rospy.loginfo("ult_deviation: "+str(ult_deviation))
        if ult_deviation < 0 or deviation < ult_deviation:
            best_gain = curr_gain
            ult_x = list(x)
            ult_y = list(y)

    # Reset x, y
    del x[:]
    del y[:]

    # if reach end of test interval
    if round(curr_gain, precision) == round(target_gain, precision):
        if precision == precision_count:
            plotPID(ult_x,ult_y,best_gain)
            rospy.signal_shutdown(0)
        curr_gain = float(best_gain - inc_gain)
        target_gain = float(best_gain + inc_gain - (float(inc_gain) / 10))
        inc_gain = (float(inc_gain) / 10)
        old_best_gain = best_gain
        precision_count += 1

    # Increment step
    curr_gain += inc_gain
    if round(curr_gain, precision) == round(old_best_gain, precision):
        curr_gain += inc_gain

    # Disable PID controller
    #pid.auto_mode = False

    # Set new PID proportional gain
    pid.Kp = curr_gain

    # Reset model state
    resetState()

    # Enable PID controller
    #pid.set_auto_mode(True, last_output=0.0)

    return 0


ziegler_started=False
def testZieglerNichols(pid,error,ult_gain,ult_period):
    global ziegler_started
    global kp
    global ki
    global kd
    if not ziegler_started:
        kp=ult_gain * 0.6
        ki=ult_gain * 1.2 / ult_period
        kd=ult_gain * 0.075 * ult_period
        pid.Kp=kp
        pid.Ki=ki
        pid.Kd=kd
        ziegler_started = True
        resetState()

    elapsed_time = time.time() - startTime
```

```
    x.append(elapsed_time)
    y.append(error)
    if elapsed_time > trial_duration:
        plotPID(x,y, str(kp) + ' Ki='+str(ki) + ' Kd='+str(kd))
        rospy.signal_shutdown(0)



def attitudeControl(attitudeData):

    global attitudeSetpoint
    global enable

    if not enable:
        return;

    # Get measured attitude as quaternion
    attitudeMeasured = np.quaternion(attitudeData.pose.pose.orientation.w,
                                     attitudeData.pose.pose.orientation.x,
                                     attitudeData.pose.pose.orientation.y,
                                     attitudeData.pose.pose.orientation.z
                                     )

    # rospy.loginfo("attitudeMeasured: " + str(attitudeMeasured))

    # Get the attitude error
    attitudeError = np.multiply( np.conjugate(attitudeMeasured), attitudeSetpoint )

    # Since 2 rotations can describe every attitude,
    # find the shorter of both rotations
    if attitudeError.w < 0:
        np.negative(attitudeError)

    # Assume derivative of attitude setpoint is proportional to the attitude error
    attitudeSetpointDerivative = Kp * attitudeError

    # Get angular rate setpoints
    rateSetpoints = np.multiply( (2 * qU) , attitudeSetpointDerivative)

    # Give the PID controllers the new setpoints
    aeleronPID.setpoint  = rateSetpoints.x
    elevatorPID.setpoint = rateSetpoints.y
    rudderPID.setpoint   = rateSetpoints.z

    # Get the Control Surface Deflections from the PID output
    msg.header.stamp = rospy.Time.now()
    msg.x = aeleronPID(attitudeData.twist.twist.angular.x)
    msg.y = elevatorPID(attitudeData.twist.twist.angular.y)
    msg.z = rudderPID(attitudeData.twist.twist.angular.z)
    publisher.publish(msg)

    # Send info to the console for debugging
    """
    rospy.loginfo(
                    "Aeleron setpoint:"+str(round(aeleronPID.setpoint, 4)) +
                    " Elevator setpoint:"+str(round(elevatorPID.setpoint, 4)) +
                    " Rudder setpoint:"+str(round(rudderPID.setpoint, 4))
                    )

    rospy.loginfo(
                    "Aeleron:"+str(round(msg.x, 4)) +
                    " Elevator:"+str(round(msg.y, 4)) +
```

```
                    " Rudder:"+str(round(msg.z, 4))
                    )
    """

    #findUltimateGain(elevatorPID, attitudeError.y)
    testZieglerNichols(elevatorPID, attitudeError.y,0.0601,0.218)


def getControl(request):
    global attitudeSetpoint
    global enable
    attitudeSetpoint = request.setPoint
    enable = request.enable
    return []

if __name__ == '__main__':
    try:

        # Init Node
        rospy.init_node('attitude_control')

        # Create attitude listener
        #rospy.Subscriber("/fixedwing/attitude", Attitude, attitudeControl)
        rospy.Subscriber("/fixedwing/truth/NED", Odometry, attitudeControl)


        # Create service
        service = rospy.Service("attitude_set" , controller_set, getControl)

        resetState()
        rospy.spin()

    #except rospy.ROSInterruptException:
    except rospy.ServiceExeption, e:
        pass
```

REFERENCES

[1] M. Gołąbek, M. Welcer, C. Szczepanski, M. Krawczyk, A. Zajdel, and K. Borodacz, "Quaternion attitude control system of highly maneuverable aircraft," *Electronics*, vol. 11, p. 3775, 11 2022.