In [ ]:
```
import numpy as np
import matplotlib.pyplot as plt
import math
def get_req_dict(name, i, j, k=1):
    req_dict_ls = []
    for index in range(i, j+1, k):
        path = name + (str(index) + ".txt")
        req_dict = {
            'IMG_REGISTER': [],
            'IMG_ROT90CLKW': [],
            'IMG_BLUR': [],
            'IMG_SHARPEN': [],
            'IMG_VERTEDGES': [],
            'IMG_HORIZEDGES': [],
            'IMG_RETRIEVE': []
        }
        with open(path, 'r') as file:
            for line in file:
                if line[0] == 'T':
                    ls = line.strip().split(' ')[1].split(':')[1].split(',')
                    ls_clean = [ls[0], ls[-3], ls[-2], ls[-1]]
                    if ls[1] == 'IMG_REGISTER':
                        req_dict['IMG_REGISTER'].append(ls_clean)
                    if ls[1] == 'IMG_ROT90CLKW':
                        req_dict['IMG_ROT90CLKW'].append(ls_clean)
                    if ls[1] == 'IMG_BLUR':
                        req_dict['IMG_BLUR'].append(ls_clean)
                    if ls[1] == 'IMG_SHARPEN':
                        req_dict['IMG_SHARPEN'].append(ls_clean)
                    if ls[1] == 'IMG_VERTEDGES':
                        req_dict['IMG_VERTEDGES'].append(ls_clean)
                    if ls[1] == 'IMG_HORIZEDGES':
                        req_dict['IMG_HORIZEDGES'].append(ls_clean)
                    if ls[1] == 'IMG_REGISTER':
                        req_dict['IMG_REGISTER'].append(ls_clean)
        req_dict_ls.append(req_dict)
    return req_dict_ls

def compute_avg_len(req_ls):
    # res = []
    # for i in range(len(req_ls)):
    request_ls = req_ls
    sum_resp = 0
    num_resp = len(request_ls)
    avg_resp = 0
    for j in range(len(request_ls)):
        sum_resp += (float)(request_ls[j][3]) - (float)(request_ls[j][2])
    avg_resp = sum_resp / num_resp
    # res.append(avg_resp)
    return avg_resp
```

```
def compute_avg_resp(req_ls):
    # res = []
    # for i in range(len(req_ls)):
    request_ls = req_ls
    sum_resp = 0
    num_resp = len(request_ls)
    avg_resp = 0
    for j in range(len(request_ls)):
        sum_resp += (float)(request_ls[j][3]) - (float)(request_ls[j][0])
    avg_resp = sum_resp / num_resp
    # res.append(avg_resp)
    return avg_resp

def draw_cdf(name_ls, data_ls, avg_resp_ls, a, b, percentile_99_ls):
    # plotting PDF and CDF
    fig, axs = plt.subplots(1, 3, figsize=(15, 5))
    for i in range(3) :
        title = f"CDF of Req Length of {name_ls[i]}"
        percentile_99_rep_fifo = np.percentile(data_ls[i], 99)
        percentile_99_ls.append(percentile_99_rep_fifo)
        count, bins_count = np.histogram(data_ls[i], bins=len(data_ls[i]))
        pdf = count / sum(count)
        cdf = np.cumsum(pdf)
        axs[i].axvline(x=avg_resp_ls[i], color='r', linestyle='--', label='A
        axs[i].axvline(x=percentile_99_rep_fifo, color='g', linestyle='--',
        axs[i].plot(bins_count[1:], cdf, label=f"{name_ls[i]} CDF", color='c
        axs[i].legend()
        axs[i].set_xlabel('time')
        axs[i].set_ylabel('value')
        axs[i].set_xlim(a, b)
        axs[i].set_title(title)
        axs[i].grid(True)
    plt.tight_layout()
    plt.show()
```

In [ ]:

```
./build/server_img -q 100 2222 > ./eval/data/s_a1.txt & ./build/client -a 10
./build/server_img -q 100 2222 > ./eval/data/s_a2.txt & ./build/client -a 10

./build/server_img -q 100 2222 > ./eval/data/s_c0.txt & ./build/client -a 10
./build/server_img -q 100 2222 > ./eval/data/s_c1.txt & ./build/client -a 10
./build/server_img -q 100 2222 > ./eval/data/s_c2.txt & ./build/client -a 10
```

a)

(1) In the first round for both `images_small` and `images_all`, `IMG_SHARPEN`, `MG_VERTEDGES`, `IMG_HORIZEDGES` all have the similar behaviors in their request length CDF, while `IMG_REGISTER`, `IMG_ROT90CLKW`, and `IMG_BLUR` each has its own unique request length CDF, as the response times of all the requests are instant.

(2) As for the predictability, as the table below shown, in both cases, `IMG_VERTEDGES` has the least predictability because the difference between its worst case request length and best case request length is the largest.

(3)

```
******* Average response time increase for each operation *******
IMG_REGISTER            2.5705118050919498
IMG_ROT90CLKW           2.9392531639843886
IMG_BLUR                2.766566188365885
IMG_SHARPEN             2.6455930576033286
IMG_VERTEDGES           2.5400287036907914
IMG_HORIZEDGES          2.7153441486423633
```

As the table below shown, here is the average response time increase for each operation calculated by avg response time of `images_all` divided by that of `images_small`

(4)

```
******* 99% tail latency increase for each operation *******
IMG_REGISTER            4.345697896790802
IMG_ROT90CLKW           5.038918728625232
IMG_BLUR                5.234059793930083
IMG_SHARPEN             5.1216740482304886
IMG_VERTEDGES           5.20440859324109
IMG_HORIZEDGES          5.116692063264637
```

As the table below shown, here is the 99% tail latency increase for each operation calculated by avg response time of `images_all` divided by that of `images_small`

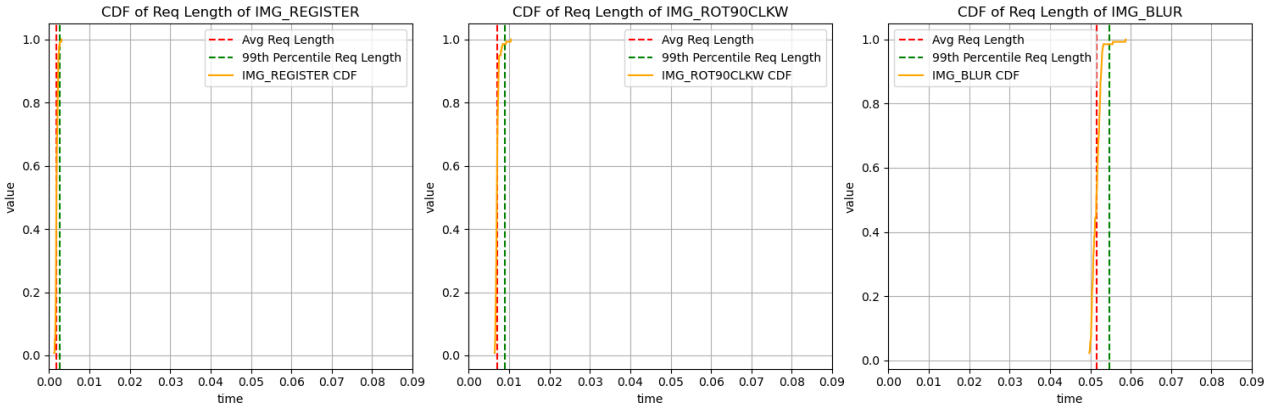
In [ ]:
```
path_a = './data/s_a'
[req_dict_ls_a1, req_dict_ls_a2] = get_req_dict(path_a, 1, 2)
```

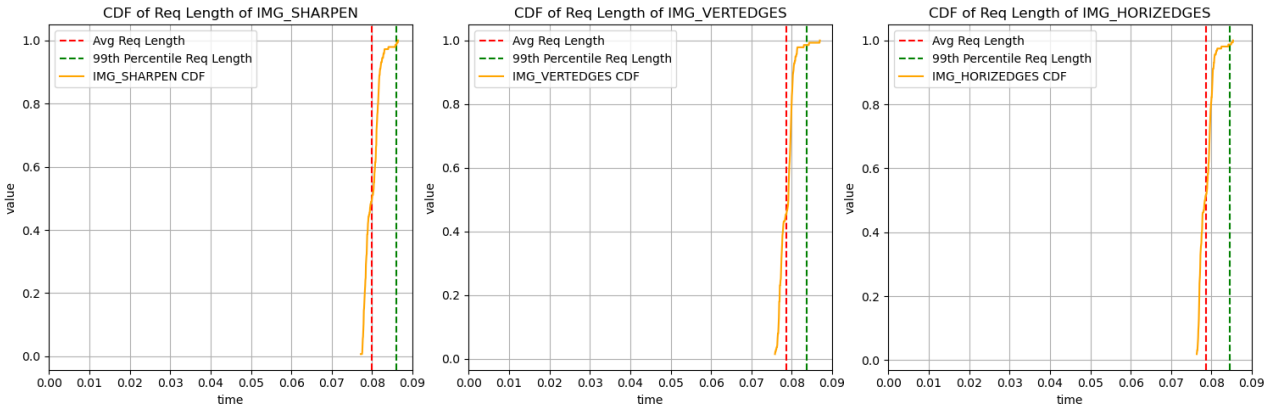
```
img_op_ls = list(req_dict_ls_a1.keys())
correct_img_op_ls = img_op_ls[0:-1]
req_a1 = [] # request raw data of RUN1
req_a2 = [] # request raw data of RUN2

avg_len_a1 = [] # avg request length list of RUN1
avg_len_a2 = [] # avg request length list of RUN2

req_t_a1 = [] # request length list of RUN1
req_t_a2 = [] # request length list of RUN2

req_len_a1 = []
req_len_a2 = []

avg_rep_a1 = [] # avg response time list of RUN1
avg_rep_a2 = [] # avg response time list of RUN2

percentile_99_a1 = []
percentile_99_a2 = []


for img_op in img_op_ls[0:3]:
    req_t_ls = []
    req_len = []
    ls = req_dict_ls_a1[img_op]
    length = len(ls)
    data = np.zeros(length)
    for i in range(length):
        len_t = (float)(ls[i][3]) - (float)(ls[i][2])
        req_t = (float)(ls[i][3]) - (float)(ls[i][0])
        req_t_ls.append(req_t)
        req_len.append(len_t)
        data[i] = len_t
    req_a1.append(data)
    avg_len = compute_avg_len(ls)
    avg_len_a1.append(avg_len)
    req_t_a1.append(req_t_ls)
    avg_rep_a1.append(compute_avg_resp(ls))
    req_len_a1.append(req_len)

for img_op in img_op_ls[3:-1]:
    req_t_ls = []
    req_len = []
    ls = req_dict_ls_a1[img_op]
    length = len(ls)
    data = np.zeros(length)
    for i in range(length):
        len_t = (float)(ls[i][3]) - (float)(ls[i][2])
        req_t = (float)(ls[i][3]) - (float)(ls[i][0])
        req_t_ls.append(req_t)
        req_len.append(len_t)
        data[i] = len_t
    req_a1.append(data)
```

```
    avg_len = compute_avg_len(ls)
    avg_len_a1.append(avg_len)
    req_t_a1.append(req_t_ls)
    avg_rep_a1.append(compute_avg_resp(ls))
    req_len_a1.append(req_len)

for img_op in img_op_ls[0:3]:
    req_t_ls = []
    req_len = []
    ls = req_dict_ls_a2[img_op]
    length = len(ls)
    data = np.zeros(length)
    for i in range(length):
        len_t = (float)(ls[i][3]) - (float)(ls[i][2])
        req_t = (float)(ls[i][3]) - (float)(ls[i][0])
        req_t_ls.append(req_t)
        req_len.append(len_t)
        data[i] = len_t
    req_a2.append(data)
    avg_len = compute_avg_len(ls)
    avg_len_a2.append(avg_len)
    req_t_a2.append(req_t_ls)
    avg_rep_a2.append(compute_avg_resp(ls))
    req_len_a2.append(req_len)

for img_op in img_op_ls[3:-1]:
    req_t_ls = []
    req_len = []
    ls = req_dict_ls_a2[img_op]
    length = len(ls)
    data = np.zeros(length)
    for i in range(length):
        len_t = (float)(ls[i][3]) - (float)(ls[i][2])
        req_t = (float)(ls[i][3]) - (float)(ls[i][0])
        req_t_ls.append(req_t)
        req_len.append(len_t)
        data[i] = len_t
    req_a2.append(data)
    avg_len = compute_avg_len(ls)
    avg_len_a2.append(avg_len)
    req_t_a2.append(req_t_ls)
    avg_rep_a2.append(compute_avg_resp(ls))
    req_len_a2.append(req_len)



print(f"Image\t\tImage operation\t\tAvg Request Length\tPredictability\t\tAv
print("-"*120)
for i in range(6):
    predit = max(req_t_a1[i]) - min(req_t_a1[i])
    print(f"images_small\t{correct_img_op_ls[i]}\t\t{avg_len_a1[i]}\t{predit
print("-"*120)
for i in range(6):
```

```
    predit = max(req_t_a2[i]) - min(req_t_a2[i])
    print(f"images_all\t{correct_img_op_ls[i]}\t\t{avg_len_a2[i]}\t{predit}\

print()
print('*'*7+ " Average response time increase for each operation "+'*'*7)
for i in range(6):
    print(f"{correct_img_op_ls[i]}\t\t{avg_len_a2[i]/avg_len_a1[i]}")

print()
print("*"*50+"\timages_small\t"+"*"*50)
print()
draw_cdf(correct_img_op_ls[0:3], req_a1[0:3], avg_len_a1[0:3], 0, 0.09, perc
draw_cdf(correct_img_op_ls[3:], req_a1[3:], avg_len_a1[3:], 0, 0.09, percent

print()
print("*"*50+"\timages_all\t"+"*"*50)
print()
draw_cdf(correct_img_op_ls[0:3], req_a2[0:3], avg_len_a2[0:3], 0, 0.6, perce
draw_cdf(correct_img_op_ls[3:], req_a2[3:], avg_len_a2[3:], 0, 0.6, percenti

print()
print('*'*7+ " 99% tail latency increase for each operation "+'*'*7)
for i in range(6):
    print(f"{correct_img_op_ls[i]}\t\t{percentile_99_a2[i]/percentile_99_a1[
```

```
Image           Image operation         Avg Request Length      Predictabili
ty              Avg Response Time
-------------------------------------------------------------------------------
-----------------------------------------
images_small    IMG_REGISTER            0.001889262773721736    0.0034210000
00003005        0.0019511605839396156
images_small    IMG_ROT90CLKW           0.007037999999996386    0.1635790000
00027   0.026492920289846046
images_small    IMG_BLUR                0.051491985185191005    0.1516639999
9998248 0.07655209629629857
images_small    IMG_SHARPEN             0.07997397241379546     0.2034529999
999677  0.09927673103448278
images_small    IMG_VERTEDGES           0.07869541726618229     0.1490780000
0003135 0.09866079136690142
images_small    IMG_HORIZEDGES          0.07857318354429904     0.1828570000
000127  0.09781381012658706
-------------------------------------------------------------------------------
-----------------------------------------
images_all      IMG_REGISTER            0.004856372262772484    0.0099759999
99994656        0.004919649635030261
images_all      IMG_ROT90CLKW           0.020686463768111504    5.4693269999
99964   3.0446696376811615
images_all      IMG_BLUR                0.1424559851851865      5.3628419999
99944   3.0596658074074092
images_all      IMG_SHARPEN             0.2115785862068974      5.6462800000
00047   2.99308839310345
images_all      IMG_VERTEDGES           0.19988861870502692     5.5313699999
99981   3.018289647482011
images_all      IMG_HORIZEDGES          0.21335323417721483     5.4603960000
00003   3.1155826645569626

******* Average response time increase for each operation *******
IMG_REGISTER            2.5705118050919498
IMG_ROT90CLKW           2.9392531639843886
IMG_BLUR                2.766566188365885
IMG_SHARPEN             2.6455930576033286
IMG_VERTEDGES           2.5400287036907914
IMG_HORIZEDGES          2.7153441486423633

************************************************      images_small
************************************************
```

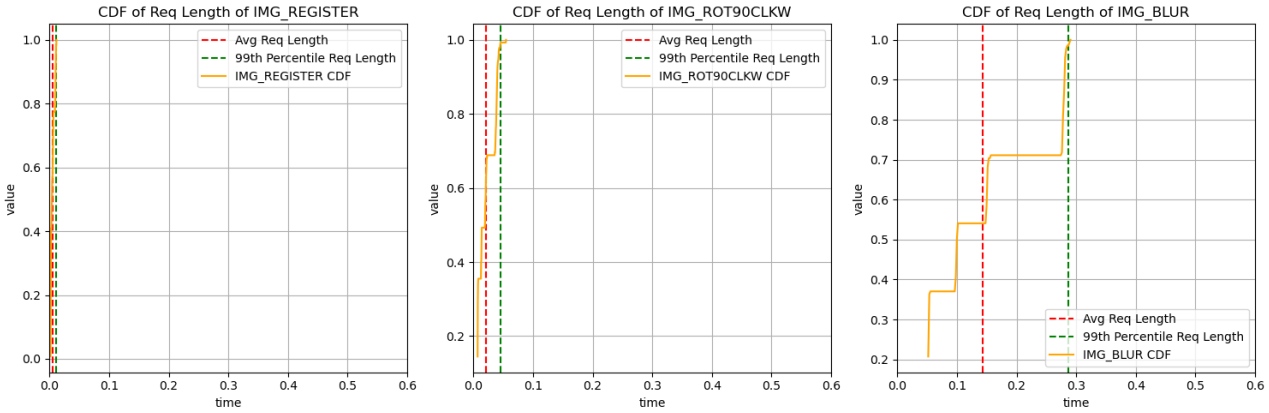

CDF of Req Length of IMG_REGISTER
Avg Req Length
99th Percentile Req Length
IMG_REGISTER CDF
CDF of Req Length of IMG_ROT90CLKW
Avg Req Length
99th Percentile Req Length
IMG_ROT90CLKW CDF
CDF of Req Length of IMG_BLUR
Avg Req Length
99th Percentile Req Length
IMG_BLUR CDF
value
time

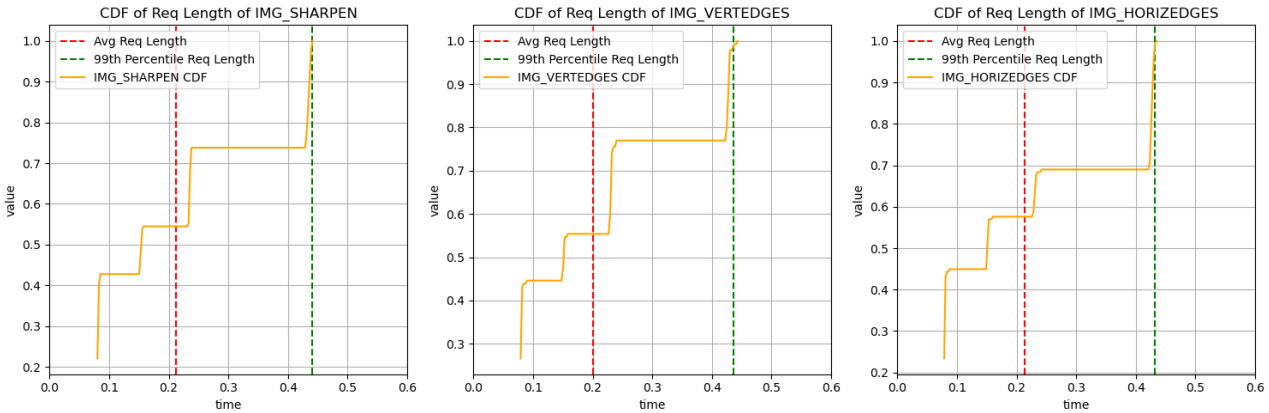

CDF of Req Length of IMG_SHARPEN
Avg Req Length
99th Percentile Req Length
IMG_SHARPEN CDF
CDF of Req Length of IMG_VERTEDGES
Avg Req Length
99th Percentile Req Length
IMG_VERTEDGES CDF
CDF of Req Length of IMG_HORIZEDGES
Avg Req Length
99th Percentile Req Length
IMG_HORIZEDGES CDF
value
time

****

images_all

****


CDF of Req Length of IMG_REGISTER
Avg Req Length
99th Percentile Req Length
IMG_REGISTER CDF
CDF of Req Length of IMG_ROT90CLKW
Avg Req Length
99th Percentile Req Length
IMG_ROT90CLKW CDF
CDF of Req Length of IMG_BLUR
Avg Req Length
99th Percentile Req Length
IMG_BLUR CDF
value
time


CDF of Req Length of IMG_SHARPEN
Avg Req Length
99th Percentile Req Length
IMG_SHARPEN CDF
CDF of Req Length of IMG_VERTEDGES
Avg Req Length
99th Percentile Req Length
IMG_VERTEDGES CDF
CDF of Req Length of IMG_HORIZEDGES
Avg Req Length
99th Percentile Req Length
IMG_HORIZEDGES CDF
value
time

```
******* 99% tail latency increase for each operation *******
IMG_REGISTER            4.345697896790802
IMG_ROT90CLKW           5.038918728625232
IMG_BLUR                5.234059793930083
IMG_SHARPEN             5.1216740482304886
IMG_VERTEDGES           5.20440859324109
IMG_HORIZEDGES          5.116692063264637
```

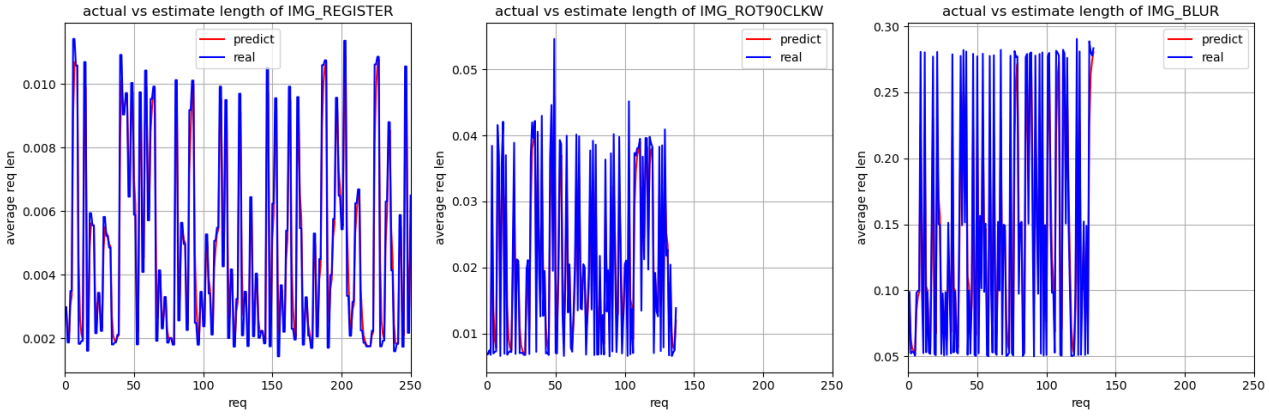
b)

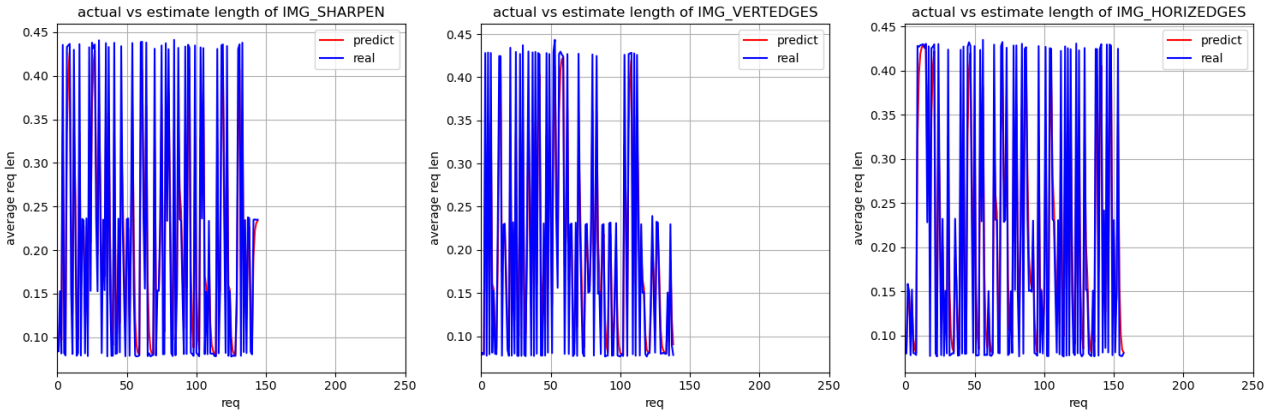
As the tables and the graphs below shown, `IMG_REGISTER` and `IMG_ROT90CLKW` have good prediction with ewma since their prediction errors are relatviely small. compared to errors of the other four.

In [ ]:
```python
# construct EWMA
def EWMA(request_len_ls, alpha):
    estimate_ls = []
    for i in range(len(request_len_ls)):
        val = request_len_ls[i]
        if(i == 0):
            estimate_ls.append(val)
        else:
            estimate = alpha * val + (1-alpha) * estimate_ls[-1]
            estimate_ls.append(estimate)
    return estimate_ls


def EWMA_ls(req_len_ls, alpha):
    res = []
    for i in range(len(req_len_ls)):
        res.append(EWMA(req_len_ls[i], alpha))
    return res

EWMA_ls_a1 = EWMA_ls(req_len_a1, 0.7)
EWMA_ls_a2 = EWMA_ls(req_len_a2, 0.7)

# compute misprediction error as the absolute value of the difference betwee
def compute_error(EWMA_ls, req_len_ls):
    res = []
    for i in range(len(EWMA_ls)):
        ls = EWMA_ls[i]
        length = len(ls)
        error_sum = 0
        for j in range(len(ls)):
            error_sum += abs(ls[j]-req_len_ls[i][j])
        error_avg = error_sum / length
        res.append(error_avg)
    return res

def draw_ewma(name_ls, EWMA_ls, req_len):
    # plotting PDF and CDF
```

```
    fig, axs = plt.subplots(1, 3, figsize=(15, 5))
    for i in range(3) :
        x = [i for i in range(len(req_len[i]))]
        axs[i].plot(x, EWMA_ls[i], color='red',  label='predict')
        axs[i].plot(x, req_len[i], color='blue',  label='real')
        axs[i].set_xlabel('req')
        axs[i].set_ylabel('average req len')
        axs[i].grid(True)
        axs[i].legend()
        axs[i].set_xlim(0, 250)
        # axs[i].set_ylim(0, 0.5)
        axs[i].set_title(f"actual vs estimate length of {name_ls[i]}")
    plt.tight_layout()
    plt.show()

# error_a1 = compute_error(EWMA_ls_a1, req_len_a1)
error_a2 = compute_error(EWMA_ls_a2, req_len_a2)
print(f"Image\t\tImg_op\t\tAvg error")
print('-'*60)

for i in range(len(error_a2)):
    print(f"images_all\t{correct_img_op_ls[i]}\t{error_a2[i]}")

draw_ewma(correct_img_op_ls[0:3], EWMA_ls_a2[0:3], req_len_a2[0:3])
draw_ewma(correct_img_op_ls[3:], EWMA_ls_a2[3:], req_len_a2[3:])
```

```
Image           Img_op          Avg error
------------------------------------------------------------
images_all      IMG_REGISTER    0.0006542344441661929
images_all      IMG_ROT90CLKW   0.00400307308751556
images_all      IMG_BLUR        0.02785583880047417
images_all      IMG_SHARPEN     0.04451490917620077
images_all      IMG_VERTEDGES   0.04084526308927787
images_all      IMG_HORIZEDGES  0.04414385885565215
```





c)

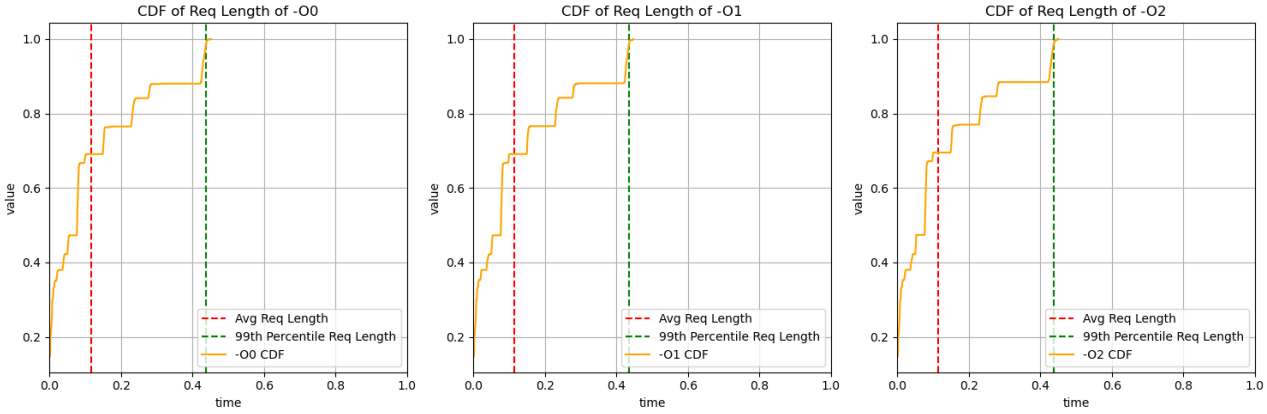
`-O<value>` flag represents the optimization level that the compiler to perform on the code being compiled. The optimization is off when `<value>=0`; the optimization comes to its first level when `<value>=1`; the optimization is futrher when `<value>=2`.

However, as can be seen from the table and the graph below, the average response time decreases as `<value>` decreases, which is consistent with what it should be.

In [ ]:
```
def get_req_ls_c(name, i, j, k=1):
    req_ls = []
    for index in range(i, j+1, k):
        path = name + (str(index) + ".txt")
        request_ls = []
        with open(path, 'r') as file:
            for line in file:
                if line[0] == 'T':
                    ls = line.strip().split(' ')[1].split(':')[1].split(',')
                    # if line[2] != 'IMG_RETRIEVE':
                    ls_clean = [ls[0], ls[-3], ls[-2], ls[-1]]
                    request_ls.append(ls_clean)
        req_ls.append(request_ls)
    return req_ls

def compute_avg_len_c(req_ls):
    res = []
    for i in range(len(req_ls)):
        request_ls = req_ls[i]
        sum_resp = 0
        num_resp = len(request_ls)
        avg_resp = 0
        print()
        for j in range(len(request_ls)):
            sum_resp += (float)(request_ls[j][3]) - (float)(request_ls[j][2]
        avg_resp = sum_resp / num_resp
```

```
        res.append(avg_resp)
    return res


path_c = './data/s_c'
req_ls_c = get_req_ls_c(path_c, 0, 2)
req_c = []
req_len_ls = []
for i in range(3):
    request_len_ls = []
    ls = req_ls_c[i]
    length = len(ls)
    data = np.zeros(length)
    for i in range(length):
        val = (float)(ls[i][3]) - (float)(ls[i][2])
        request_len_ls.append(val)
        req_t = val
        data[i] = req_t
    req_c.append(data)
    req_len_ls.append(request_len_ls)
# print(req_c)
avg_len_c = compute_avg_len_c(req_ls_c)
# print(avg_rep_c)
name_ls_c = ["-O0", "-O1", "-O2"]
print("Makefile setting\tAverage Request Length")
print("-"*45)
for i in range(3):
    len_ls = req_len_ls[i]
    # print(len_ls)
    print(f"{name_ls_c[i]}\t\t\t{avg_len_c[i]}")
draw_cdf(name_ls_c, req_c, avg_len_c, 0, 1, [])
```

```
Makefile setting        Average Request Length
---------------------------------------------
-O0                     0.11533166000000052
-O1                     0.11469311599999878
-O2                     0.11379777300000068
```



In [ ]: