Algorithm Memo: Non-Linear Filter for Video Stabilization

This memo is to describe the design of non-linear filter in video stabilization algorithm, the reference is from [A Non-Linear Filter for Gyroscope-Based Video Stabilization]

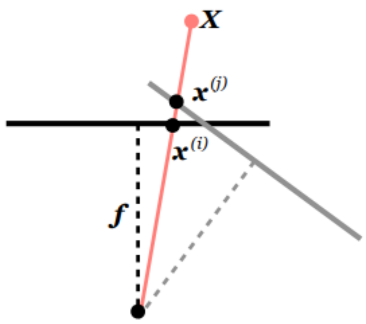
Transformation from unstable to stable camera orientation:

For an object X in world coordinate which project the coordinate to image with camera orientation

$trans\_matrix = cal\_trans\_matrix(p\_cam\_orien, v\_cam\_orien)$

$x_{stable} = x_{unstable} \cdot trans\_matrix$

> $x_{unstable}$ is the coordinate of original image
>
> x_{stable} is the coordinate of stable image
>
> v_cam_orien is virtual camera orientation
>
> p_cam_orien is physical camera orientation



Definition

- **camera orientation**: a trajectory of a camera
  - **physical camera orientation**: $p[k]$

    a real, physical camera orientation
  - **virtual camera orientation**: $v[k]$

    a smoother physical camera orientation
- **camera velocity**: rotation change of a camera
  - **physical camera velocity**: $p\Delta[k]$

    physical camera rotation change
  - **virtual camera velocity:** $v\Delta[k]$

    virtual camera rotation change
- **transformation matrix:** the transformation matrix is to project coordinate from physical camera to virtual camera coordinate.

Equation

- **physical camera orientation**

  $p[k] = Quaternion.integrate(p[k-1], angular\_velocity, \Delta t)$

- **physical camera velocity**

  $p\Delta[k-1] = p^*[k-1].p[k]$, $p^*[k-1]$ $is\ conjugate\ of\ p[k-1]$

- **virtual camera orientation**

  $v[k] = v[k-1].v\Delta[k-1]$

- **virtual camera velocity**

  $v\Delta[k] = slerp(p\Delta[k-1], v\Delta[k-1], \alpha)$

  α is low-pass filter coefficient

- **transformation matrix**

  $trans\_matrix = KR_vR_p^{-1}K^{-1}$

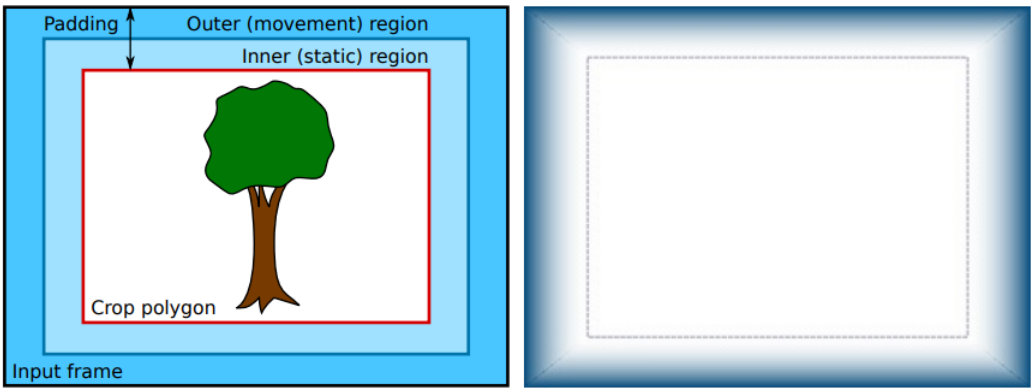
  R_v and R_p are virtual and physical orientation matrix respectively.

  K is camera intrinsic matrix

Non-linear filter Design

All concept in paper is to have a coefficient α

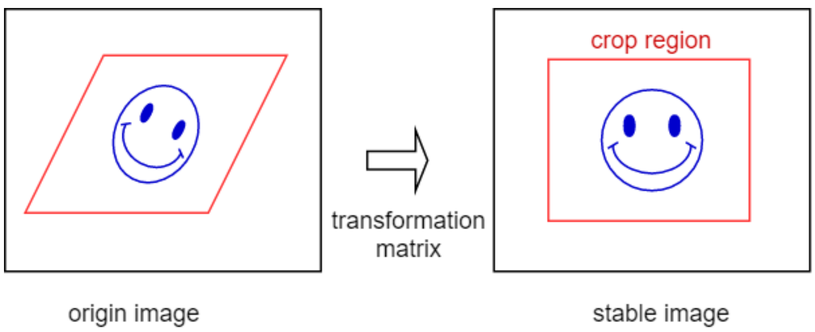
α differs by crop polygon location



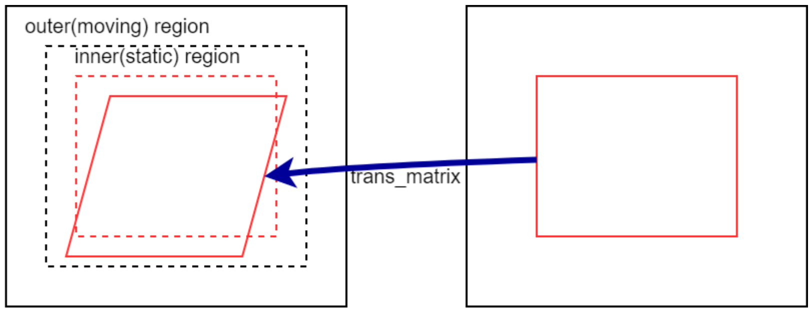
- **Crop Polygon**

Crop polygon is computed from crop region of origin image to a stable image

```
crop polygon = crop_region*trans_matrix
```

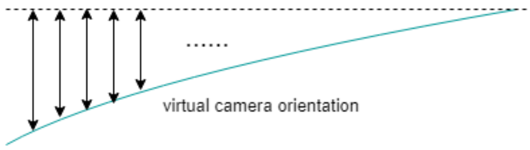


- **inner region**:



to be a static region, which reduce the virtual camera velocity in this area

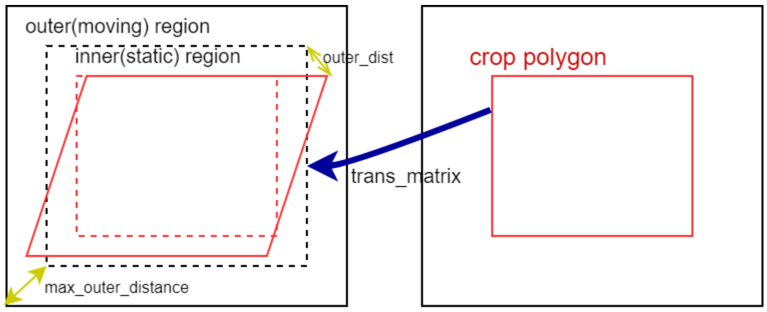
$$virtual\_angle_i = d \times virtual\_angle_{i-1}, d\ is\ damping\ coefficient$$



- **outer region:**

paper method:

I don't like it :(...



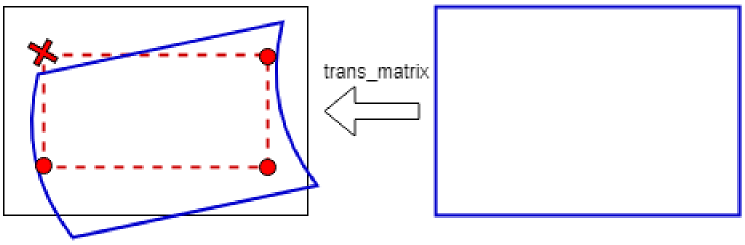
$\alpha = (1 - \omega^\beta)$

$\omega = \frac{outer\_distance}{max\_outer\_distance}$

refinement

  - boundary condition

    if there are any coordinate of the crop region out of full-frame polygon, it would be out of boundary.



The out-of-boundary condition occurs when any vertex of crop ROI out of the frame polygon, so we adjust the low-pass filter smooth coefficient by the distance of frame_polygon and crop ROI.

the low pass filter coefficient α is:

$\omega = \frac{min\_vertices\_distance}{max\_distance}$

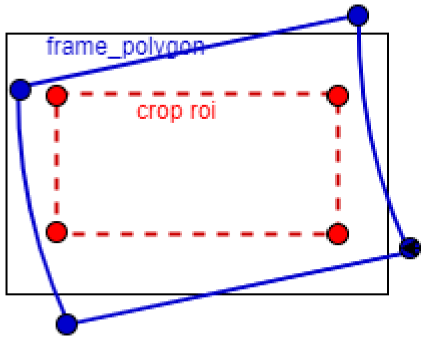
for limit low-pass filter, I apply boundary for low-pass filter α in $[\alpha_{min}, \alpha_{max}]$

$\alpha\_ratio = \omega^{\beta}$

$\alpha = \alpha\_ratio * \alpha_{max} + (1 - \alpha\_ratio) * \alpha_{min}$

and apply another lpf to low-pass filter coefficient α to avoid too many uncontinuous out-of boundary condition.

$\alpha[k] = 0.95 * \alpha[k-1] + 0.05 * \alpha[k]$



Boundary Limitation

- **boundary control**

  In the out of the boundary condition, we have two criteria to converge physical and virtual camera orientation

  - no rolling shutter correction

    All compensation is eliminated includes rolling shutter correction, as the frame polygon hits the crop region. In the out-of-boundary condition,the most import thing is to converge the difference between physical and virtual camera trajectory. So we stop the rolling shutter correction in the out-of-boundary condition.

  - remain virtual camera velocity with physical camera velocity

    $pv\Delta[k-1] = p[k-1]^{*}.v[k-1]$

    $v[k] = p[k].pv\Delta[k-1]$

Look-ahead Filter

The low-pass filter window size span by projecting the virtual camera orientation forward in time and comparing it to the actual orientation at "future" time.

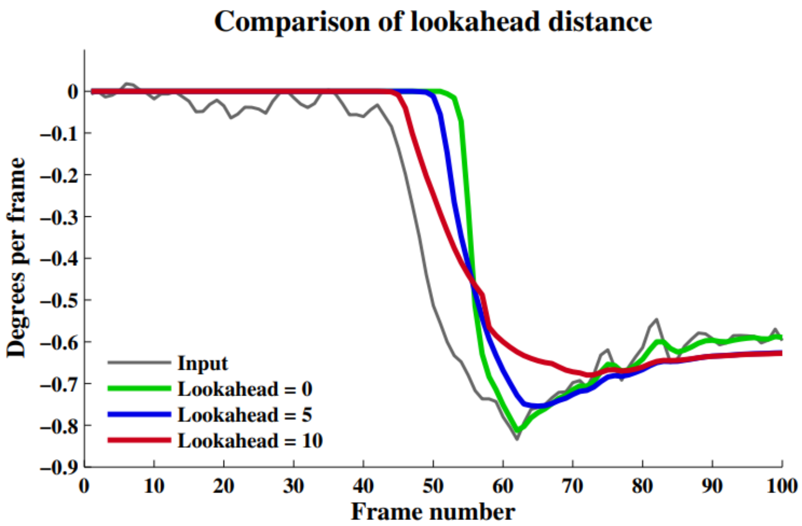


Fig. 3. Comparison of paths for varying lookahead distances. Larger lookahead values require more data to be buffered, but produce smoother output paths.

Hypothesis:

paper

forward filter

$v\Delta(k) = slerp(p\Delta(k), v\Delta(k-1), \alpha)$

look-ahead filter:

Let a be the number a frames to look ahead, the hypothesis:

$v(k+a) = v(k-1).\, v\Delta(k)^{a+1}$

and $v\Delta(k)$ can be updated:

$v\Delta(k) = slerp(v\Delta(k+a), v\Delta(k), \gamma)$

refinement

forward filter

$v\Delta(k) = slerp(p\Delta(k), v\Delta(k-1), \alpha)$

look-ahead filter:

for i = a to 0

$v\Delta(k) = slerp(p\Delta(k)^i, v\Delta(k), \gamma)$

Data Structure

the data structure have to fit both forward filter and look-ahead filter, as look-ahead number a=0, which means forward filter.

there are queues in the filter to buffer history data:

- p_cam_orien queue

  physical camera orientation buffer, include knee points orientation of each frame.

- v_cam_orien queue

  virtual camera orientation buffer

- $v\Delta$ queue

  virtual camera velocity buffer

- frame queue

  frame buffer

Queue	0	1	2	3	4
p_cam_orien_buffer					
v_cam_orien_buffer					
v_cam_velocity_buffer					
frame_buffer					

Queue Handler

let set a = 5, so each queue size would be 5

Initialization:

```
# initialize buffer
v_cam_orien_buffer = deque(maxlen=a)
p_cam_orien_buffer = deque(maxlen=a)
v_cam_velocity_buffer =  deque(maxlen=a)
frame_buffer = deque(deque(maxlen=a))
# initialize camera orientation and velocity
prev_v_cam_orien = Quaternion()
prev_p_cam_orien = Quaternion()
prev_v_cam_velocity = Quaternion()
```

- i = 0

  $p[0] = intergrate(p_{prev}, \omega[0], \Delta t)$

  $p\Delta[0] = p[0].\, p^*_{prev}$

  $v\Delta[0] = slerp(p\Delta[0], v\Delta_{prev}, alpha)$

  $v[0] = v_{prev}.\, v\Delta[0]$

  push to buffer:

  $frame[0], p[0], v[0], v\Delta[0]$

  $p_{prev} = p[0]$

  $v_{prev} = v[0]$

  $v\Delta_{prev} = v\Delta[0]$

Queue	0	1	2	3	4
p_cam_orien_buffer	$p[0]$				
v_cam_orien_buffer	$v[0]$				
v_cam_velocity_buffer	$v\Delta[0]$				
frame_buffer	frame[0]				

frame_buffer	frame[0]				

- i = 1
- i = 2
- i = 3

  ...

- i = 4

  $p[4] = intergrate(p_{prev}, \omega[4], \Delta t)$

  $p\Delta[4] = p[4] . p^*_{prev}$

  $v\Delta[4] = slerp(p\Delta[4], v\Delta_{prev}, alpha)$

  $v[4] = v_{prev} . v\Delta[4]$

  push to buffer:

  $frame[4], v[4], v\Delta[4]$

  $p_{prev} = p[4]$

  $v_{prev} = v[4]$

  $v\Delta_{prev} = v\Delta[4]$

Queue	0	1	2	3	4
p_cam_orien_buffer	$p[0]$	$p[1]$	$p[2]$	$p[3]$	$p[4]$
v_cam_orien_buffer	$v[0]$	$v[1]$	$v[2]$	$v[3]$	$v[4]$
v_cam_velocity_buffer	$v\Delta[0]$	$v\Delta[1]$	$v\Delta[2]$	$v\Delta[3]$	$v\Delta[4]$
frame_buffer	frame[0]	frame[1]	frame[2]	frame[3]	frame[4]

- i = 5

$p[5] = intergrate(p_{prev}, \omega[5], \Delta t)$

$p\Delta[5] = p[5] . p^*_{prev}$

$v\Delta[5] = slerp(p\Delta[5], v\Delta_{prev}, \alpha)$

$v[5] = v_{prev} . v\Delta[5]$

if (queue.size() >= a)

{

$v\Delta[0] = slerp(v\Delta[0], v\Delta[5], \gamma)$

$v[1] = v[0] . v\Delta[0]$

trans_matrices[1] = cal_trans_matrices(v[1],p[1])

}

push to buffer:

$frame[5], v[5], v\Delta[5]$

$p_{prev} = p[5]$

$v_{prev} = v[5]$

$v\Delta_{prev} = v\Delta[5]$

Queue	0	1	2	3	4
p_cam_orien_buffer	p[1]	p [2]	p [3]	p [4]	p [5]
v_cam_orien_buffer	v[1]	v [2]	v[3]	v[4]	v[5]
v_cam_velocity_buffer	$v\Delta[1]$	$v\Delta[2]$	$v\Delta[3]$	$v\Delta[4]$	$v\Delta[5]$
frame_buffer	frame[1]	frame[2]	frame[3]	frame[4]	frame[5]

Pseudo code:

```
# integrate physycal camera orientation
p_cam_orien = integrate_p_cam_orien(prev_p_cam_orien,angular_vecloty, timestamp)
# calculate physical camera velocity
p_cam_velocity = p_cam_orien*prev_p_cam_orien.conjugate
# virtual camera velocity calculation in foward direction
current_v_cam_velocity= slerp(p_cam_velocity,prev_v_cam_velocity,alpha)

# virtual camera velocity calculation in look-ahead direction
if len(v_cam_velocity_buffer)>= a:

    foward_v_cam_velocity = v_cam_velocity_buffer[0]
    foward_v_cam_velocity =
slerp(current_v_cam_velocity,foward_v_cam_velocity,gamma)

    # virtual camera orientation integration
    v_cam_orien_buffer[1] = v_cam_orien_buffer[0]* forward_v_cam_velocity
    trans_matrices =
cal_trans_matrices(v_cam_orien_buffer[1],p_cam_orien_buffer[1])

# push orientation and velocity to buffer
p_cam_orien_buffer.push_back(p_cam_orien)
v_cam_orien_buffer.push_back(v_cam_orien)
v_cam_velocity_buffer.push_back(current_v_cam_velocity)

# store current to previous orientation and velocity
prev_v_cam_orien = v_cam_orien
prev_p_cam_orien = p_cam_orien
prev_v_cam_velocity = current_v_cam_velocity
```

Transformation Matrix

$trans\_matrix = KR_vR_p^{-1}K^{-1}$

to get the virtual camera coordinate, we have to inverse physical camera coordinate then rotate with virtual camera.

$x_v = x_p.p\_cam\_orien^{-1}.v\_cam\_orien$

so that

$R_vR_p^{-1} = p\_cam\_orien^{-1}.v\_cam\_orien$

Rolling Shutter Correction

Timing of inter-frame and intra-frame duration

inter-frame duration

```
inter-frame_start_ts =
vsync_timestamp - vsync_duration + top_blanking x dt - prev_exptime*0.5

inter-frame_end_ts =
vsync_timestamp + top_blanking x dt - exptime*0.5
```

intra-frame duration

```
intra-frame_start_ts = vsync_timestamp + top_blanking x dt - exptime*0.5

intra-frame_end_ts = vsync_timestamp + (top_blanking + image_height) x dt -
exptime*0.5
```