Computational Techniques for Revealing Physiological and Biometric Signals Hidden in Standard Video Streams for Remote, Contactless Monitoring of Cardiovascular Health & Identity Authentication

Abstract

With the rising cost of healthcare and the ubiquity of the internet, telemedicine is becoming a necessary and viable option. Physicians need to be able to remotely monitor a patient's well-being and have foolproof identity verification systems to avoid healthcare fraud. Unfortunately, remote monitoring of vital signs requires the patient to wear specialized equipment, which is expensive and obtrusive, limiting its use. My research focused on developing computational techniques for contactless assessment of vital signs and biometrics from ordinary webcam/smartphone video.

Research indicated that videos capture minute temporal variations in color, intensity, and motion at a pixel level that are imperceptible to humans but easily distinguishable by computers. For instance, the human face becomes redder as blood is pumped by the heart, the skin on the wrist rises slightly with each pulse beat, and the ridges in our fingerprints reflect light at different intensities.

Based on the research I successfully developed computational techniques to detect and magnify the subtle variations in color, intensity, and motion in videos. I validated these techniques by developing three applications:

1. Continuous, contactless, remote video monitoring of patient's cardiovascular health
2. Contactless measurement of respiration rate with web/smartphone camera
3. Extraction of fingerprints along with "liveness" detection from video stream for foolproof identity verification

The innovative algorithms developed rely on computation, rather than optics, to selectively magnify hidden signals in ordinary videos to unlock and visualize a new world of previously invisible information. In addition to health care, the techniques have wide-ranging applications in biology, structural analysis, and mechanical engineering.

Research Problem

With rising healthcare costs, telemedicine is becoming a necessity. Research indicates that telemedicine can save $6 billion/year for USA and more importantly, 64% of Americans are willing to have a video visit with a doctor. However, despite the pervasive use of smartphones and the rapid adoption of internet or phone based video conferencing applications, telemedicine remains an elusive goal since:

- Basic diagnostics and assessment of vital signs requires patients to have access to specialized equipment
- Chronically ill or aftercare patients requiring continuous monitoring of cardiovascular health need expensive and obtrusive devices onsite. Hardware solutions like Laser/Microwave Doppler Radars and thermal imaging are expensive and not viable for general use.
- Remote identify verification using standard biometrics such as fingerprint is easy to spoof and can lead to medical fraud

Research Goal and Requirements

My goal was to develop software techniques for remote, contactless, video-based assessment of cardiovascular health and spoof-proof identity verification to make telemedicine viable.

Since video-conferencing is the foundation for telemedicine, I focused on developing video-based techniques for diagnosis and monitoring three specific areas:

1. Continuous, contactless evaluation of cardiovascular health using standard webcam video
2. Assessment of vital signs and respiration rate from video
3. Spoof-proof identity verification for remote patient authentication to avoid fraud

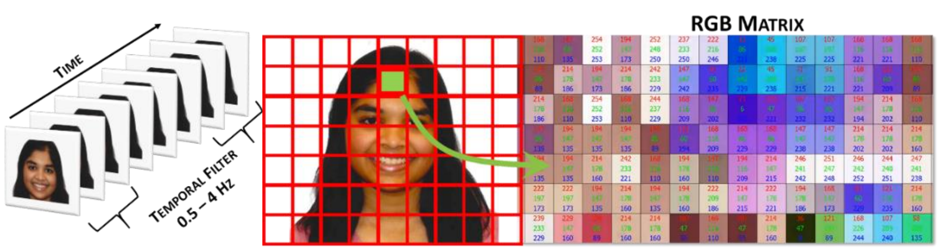
Development

With the ubiquity of smartphones and cameras, videography has become a huge part of our everyday life. The videos contain invaluable information, at a pixel level, that is imperceptible to the human eye such as blood flows to the face making it redder, or the variation in light intensity as it bounces off the ridges in our fingerprints, or the tiny movement of the chest for respiration. These subtle motions or changes in intensity and color can be magnified by software to reveal critical health and physiological information.

I used sophisticated computer vision techniques to selectively magnify the temporal, variations in color, intensity, and motion in videos to reveal vital information. The software was developed in Python using OpenCV Computer Vision library and related packages. New algorithms were designed to enable real-time processing and three apps were developed that can be used in telemedicine (see Appendix for implementation details):

1. Cardiac Pulse From video stream

To measure cardiac pulse, I leveraged the fact that the skin gets redder by ~0.3 - 0.5% in rhythm with heart beat. By analyzing temporal variations in the luminance of skin at a specific location, the heart rate can be calculated. I decomposed the video stream into frames, filtered the frames of interest and tracked the temporal pixel luminance changes on green channel to capture the color change corresponding to the heart rate. The ambient light & skin-tone differences were normalized prior to applying Fast Fourier Transform to extract cardiac pulse.

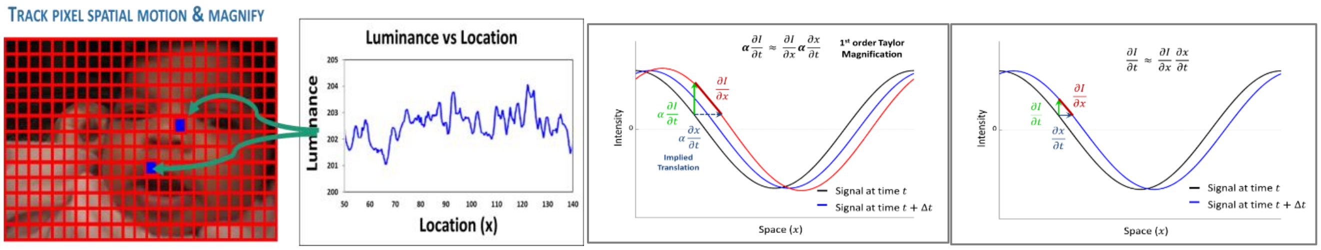


2. Remote respiration rate assessment

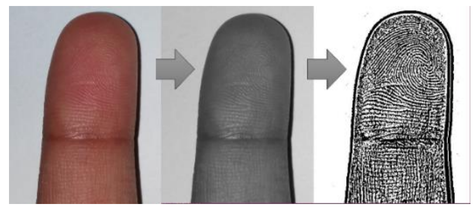
To measure respiration rate the rhythmic motion of the abdomen was selectively magnified. The Spatial motion of specific pixels in videos were magnified by increasing temporal variation by applying the 1^{st} order Taylor series as demonstrated by the Euler[1] magnification technique.[2]

[1] "Eulerian Video Magnification." Eulerian Video Magnification -- Yan Gu. N.p., n.d. Web. 10 Mar. 2017

[2] Neal Wadhwa, Hao-Yu Wu, Abe Davis, Michael Rubinstein, Eugene Shih, Gautham J Mysore, Justin G Chen, Oral Buyukozturk, John V Guttag, William T Freeman, Frédo Durand. "Eulerian Video Magnification and Analysis." ACM. N.p., 01 Jan. 2017. Web. 11 Mar. 2017



3. Fingerprint with Liveness Detection



Fingerprint extraction[3] from live video was enabled by using Contrast Limited Adaptive Histogram Equalization (CLAHE) image processing technique to enhance contrast and edges. Fingerprint based authentication was made more secure with "liveness" detection by verifying the pulse (using color change technique) to avoid spoofs with 3-D printed fingers or pre-recorded video/image.

Results

Three innovative apps were successfully developed to enable telemedicine solutions. Since the algorithms can be applied to solve a variety of problems, I also refactored the code to create a library called "VitalSight."

The VitalSight Computer Vision Library reduces the time to develop complex computer vision apps that reveal a world of invisible information hidden in ordinary videos. The library provides powerful modules that uncover hidden signals in videos to enable rapid development of apps in fields such as healthcare, security, finance and engineering. The techniques work with both live and recorded video streams.

1. **The Cardiac Pulse App** can continuously monitor the cardiac pulse over video in real-time. The app was tested by comparing readings with an FDA approved Pulse Oximeter under different environmental conditions including natural light, fluorescent light, varying ambient light, resting and heart rate after workout and on different skin tones (see Appendix). The app can eliminate the need for expensive or obtrusive equipment and serve as a low cost alternative to ECG to detect atrial fibrillation and cardiac issues.
2. **The Respiration App** applies temporal filters to process frames in the expected breaths/minute range for: infants 10 – 50 /min (0.16 – 0.83 Hz) and adults 10 – 30 /min (0.16 – 0.5 Hz) and magnifies abdomen motion from 50 to 100 times to enable easy measurement of respiration rate.
3. **The Fingerprint App** was field tested in Tanzania using simple feature phones and is being used for live extraction of fingerprints and analysis.

Future Enhancements

The techniques developed have applications in a variety of fields such as security, finance, biology, mechanical & civil engineering. The heart rate monitoring app can be used for emotion detection for security and law enforcement; Motion magnification can enable new class of apps to analyze the structural vibrations in buildings and bridges, vibrations in heavy machinery and aircraft wings; Fingerprint with liveness detection can be used for spoof-proof identity authentication for finance and remote banking. In future, I plan to add machine learning capabilities to make intelligent decisions for detecting sleep apnea and heart arrhythmia.

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[3] "Scaling-robust Fingerprint Verification with Smartphone Camera in Real-life Scenarios - IEEE Xplore Document." *Scaling-robust Fingerprint Verification with Smartphone Camera in Real-life Scenarios - IEEE Xplore Document*. N.p., n.d. Web. 10 Mar. 2017

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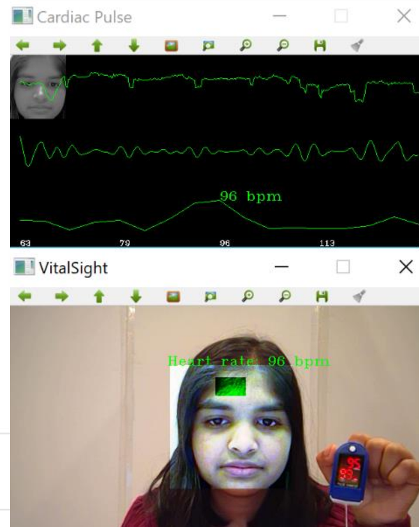
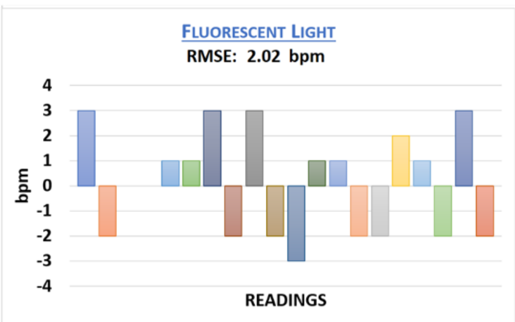
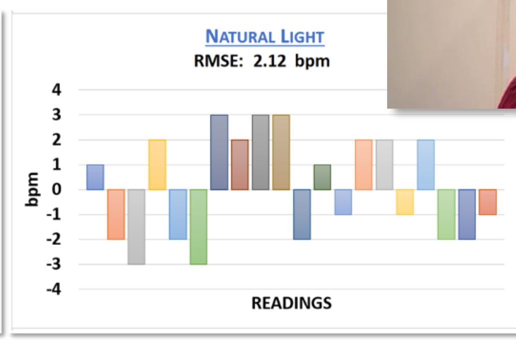
Appendix

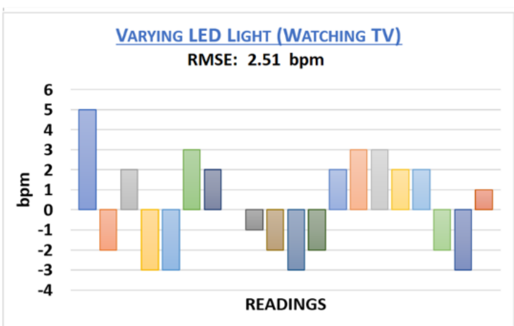


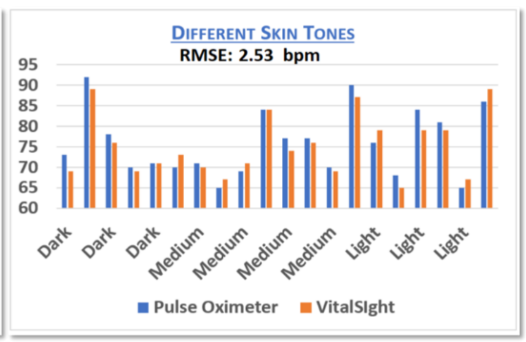
Test results for cardiac pulse under varying conditions:

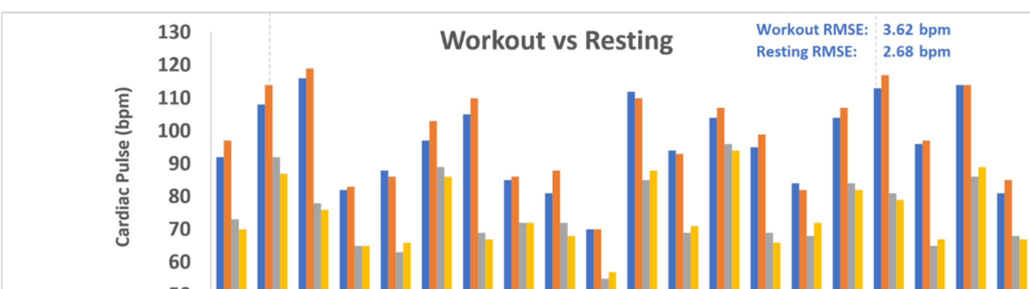
Readings from the app were compared with FDA approved pulse oximeter and Root Mean Square Error (RMSE) was calculated.











	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Workout Pulse Oximeter	92	108	116	82	88	97	105	85	81	70	112	94	104	95	84	104	113	96	114	81
Workout VitalSIght	97	114	119	83	86	103	110	86	88	70	110	93	107	99	82	107	117	97	114	85
Resting Pulse Oximeter	73	92	78	65	63	89	69	72	72	55	85	69	96	69	68	84	81	65	86	68
Resting VitalSight	70	87	76	65	66	86	67	72	68	57	88	71	94	66	72	82	79	67	89	67

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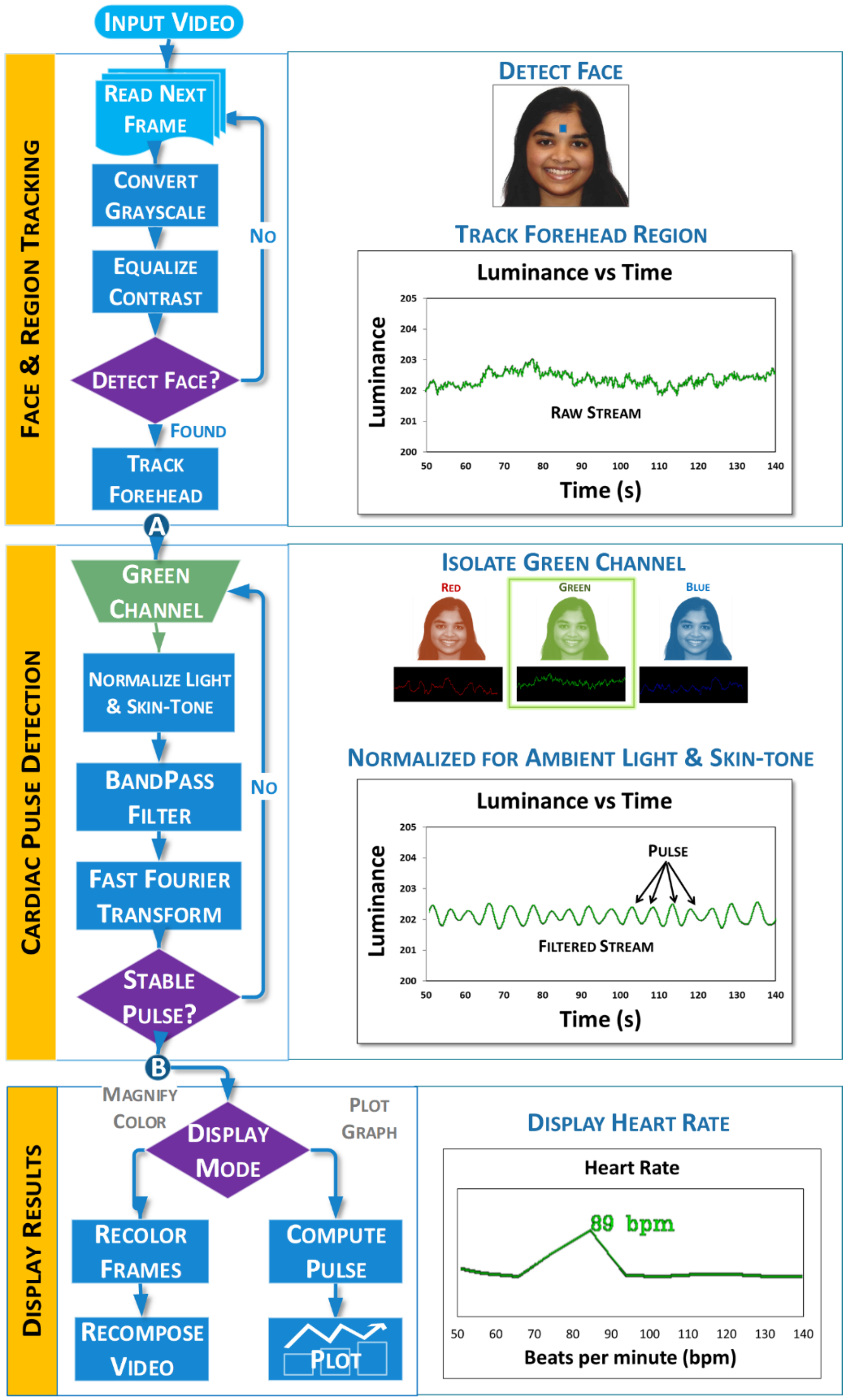

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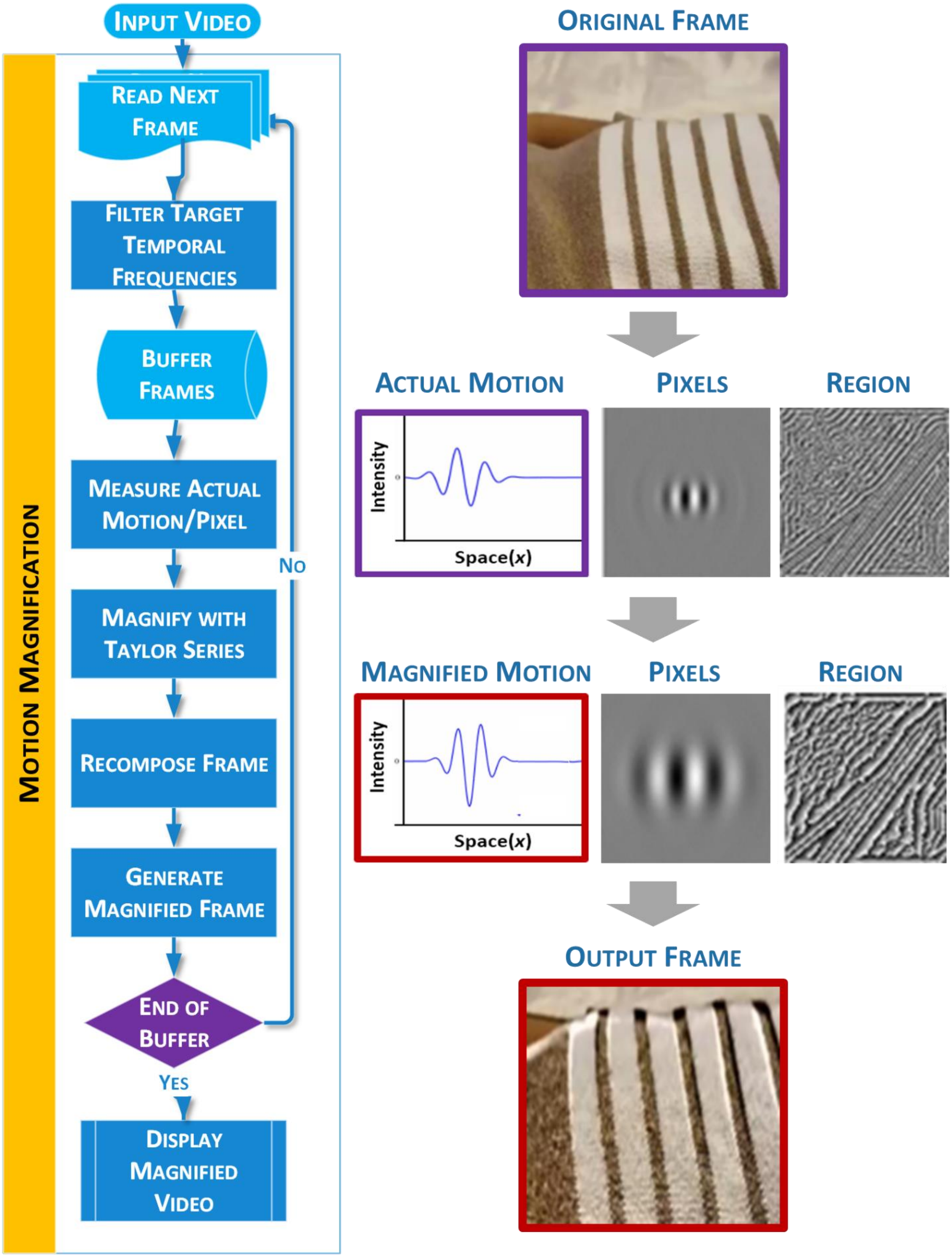

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